# SUMMARY REPORT No. 2

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# OF A HEAVY-METAL-REFLECTED

# FAST-SPECTRUM CRITICAL ASSEMBLY

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# FOREWORD

The work described herein was performed by Atomics International, a Division of North American Rockwell Corporation, under Contract NAS3-14421, with Mr. Paul G. Klann, Nuclear Systems Division, NASA Lewis Research Center, as Project Manager. This work represents a continuation of a program which was reported in NASA-CR-72820 under Contract NAS3-12982.

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## ABSTRACT

A zero-power critical assembly was designed, constructed, and operated under a previous NASA-funded program for the purpose of conducting a series of benchmark experiments dealing with the physics characteristics of a UN-fueled, $Li^7$-cooled, Mo-reflected, drum-controlled compact fast reactor for use with a space-power electric conversion system (see NASA-CR-72820). The range of the previous experimental investigations has been expanded to include the reactivity effects of (1) surrounding the reactor with 15.24 cm (6 in.) of polyethylene, (2) reducing the heights of a portion of the upper and lower axial reflectors by factors of 2 and 4, (3) adding 45 kg of W to the core uniformly in two steps, (4) adding 9.54 kg of Ta to the core uniformly, and (5) inserting 2.3 kg of polyethylene into the core proper and determining the effect of a Ta addition on the polyethylene worth. In addition, a determination of the spectrum at the core-reflector interface was made. Finally, the power distribution, control characteristics, and critical mass of a version of the reactor using 6 unfueled, $B_4C$-loaded control drums were ascertained.

# SUMMARY

A zero-power critical assembly was designed, constructed, and operated under a previous NASA-funded program for the purpose of conducting a series of benchmark experiments dealing with the physics characteristics of a UN-fueled, $Li^7$-cooled, Mo-reflected, drum-controlled compact fast reactor for use with a space power electric conversion system (see Reference 1). The critical assembly, which is a close geometrical simulation of the reference reactor, consists of a close packed, six-pointed, star-shaped array of 181 Ta-clad pin-type elements fueled with uranium metal and surrounded axially and radially by a Mo reflector. Nested between the points of the star-shaped core are six control drums each containing eleven fuel elements, a Mo reflector, and a Ta absorber segment.

The initial experimental program, which was reported in NASA-CR-72820, consisted basically of measuring the differential neutron spectra and the changes in critical mass that accompanied the stepwise addition of $Li_3^7N$ (used to simulate the $Li^7$ coolant and the nitride in the fuel of the reference reactor), Hf, Ta, and W to a basic core which had a uniform distribution of uranium fuel. In addition, studies were carried out on power distributions, control characteristics, neutron lifetime, and reactivity worths of numerous absorber, structural, and scattering materials. A three-zoned, power-flattened configuration was also assembled and tested to determine various physics parameters.

The objectives of the current program are to provide additional experimental data on the physics and safety characteristics of the reference reactor. In particular, the range of experimental investigations has been expanded to include the reactivity effects of (1) surrounding a power-flattened version of the reactor on top, bottom, and sides with 15.24 cm (6 in.) of polyethylene; (2) reducing the lengths of portions of the upper and lower axial reflectors in a uniformly loaded core by factors of 2 and 4; (3) adding 45 kg of W to the core uniformly in two steps; (4) adding 9.54 kg of Ta to the core uniformly; and (5) inserting 2.3 kg of polyethylene into the core proper. In addition, a determination of the spectrum at the core-reflector interface was made. Finally, the power distribution, control characteristics, and critical mass of a version of the reactor incorporating six unfueled $B_4C$-loaded control drums were measured.

By surrounding the power-flattened version of the cylindrical reactor on the sides, top, and bottom by an approximately 15.24-cm(6-in.)-thick polyethylene shield, an increase in the system reactivity of $1.06 was observed. The removal of the entire top section of the polyethylene shield as well as a portion of the lower section decreased the reactivity of the system by 15.6¢. The reactivity worth of each drum in the fully-shielded core averaged $2.37 and the measured worth of all drums was found to be $15.36, both values being essentially identical to the corresponding results for the power flattened core without the polyethylene shield in place.

The reduction of the height of the cylindrical part of the two-piece axial Mo reflector from 10.00 cm (3.94 in.) to 4.90 cm (1.93 in.) in a uniformly loaded version of the reactor reduced the system reactivity by about $1.57, whereas a reduction in the cylindrical part from 4.90 cm (1.93 in.) to 2.45 cm (0.97 in.) resulted in a decrease in reactivity of $1.31. The height of the annular Mo reflector piece was left unchanged for these measurements. Similarly, a reduction in reactivity occurred upon adding 9.54 kg of Ta to a uniformly loaded version of the core already containing large quantitites of Ta and incorporating full-length axial reflectors. In the latter case, the Ta that was added was found to be worth -17.6¢. The addition of W to a uniformly loaded version of the core added reactivity, the values being +71.6¢ for 29.4 kg and +$1.22 for 44.5 kg. No tungsten was in the core prior to these additions.

In order to simulate reactivity effects that accompany a hypothetical flooding of the core, 360 polyethylene strips (2.3 kg) were added more or less uniformly to the core in several steps. In general, the reactivity worth of each strip (6.193 gm) was found to be about 1.16¢, thus indicating a total reactivity change for all strips of about $4.11.

A measurement of the differential neutron spectrum at the interface of the core and upper reflector of a uniformly loaded version of the core was conducted and showed a spectrum very similar to that previously determined at the center of the same core configuration, although some flattening of the peak in the 400 to 800 kev region may be in evidence.

A version of the reference reactor incorporating six unfueled control drums was assembled using $B_4C$ in the volume of the drum previously occupied by fuel,

and Mo plates in the volume of the drum previously occupied by Ta. A critical mass of 141.43 kg of U was measured, where the fueled zone corresponded to the 181 stationary fuel elements in the reference design and the $B_4C$ section in each drum was turned full-out. The average worth of one $B_4C$ control drum was found to be about \$1.93, and the worth of all drums ganged was determined to be \$11.98. From a power distribution measurement, the ratio of the power at the core center to the power at the outer edge of the $B_4C$ drum sector at the midplane was found to be 9.15 when the drum was turned such that the $B_4C$ was full-out. This ratio, as it applied to the inner edge of the $B_4C$ sector in the same orientation, was 4.10.

In general the experimental results were in reasonably good agreement with values calculated by NASA. Whenever, in the course of this program, an experiment that duplicated a previous measurement was conducted, the agreement between comparable values was very good.

# I. INTRODUCTION

## A. BACKGROUND

The National Aeronautics and Space Administration has initiated a program for the purpose of designing a compact fast reactor for use in the generation of electric power in space. The reactor, which employs advanced concepts, is expected to operate at several megawatts, and is characterized by the exclusive use of high-temperature, high-strength refractory materials for structural, cladding, and reflecting purposes. The design goals for the reactor call for operation at high temperatures (1273°K) for periods of time of the order of 5 years.

An extensive series of neutronic calculations is being carried out by NASA on a reference design of one such reactor, a design that consists of a close-packed array of T-111 honeycomb tubes into which fuel pins are placed. These T-111 tubes are 2.159 cm (0.850 in.) in outside diameter (OD) and have a wall thickness of 0.0254 cm (0.010 in.). The fuel pin is also comprised of T-111 tubing which is 1.905 cm (0.750 in.) OD, has a wall thickness of 0.147 cm (0.058 in.), and is lined on the inside with a 0.013-cm(0.005-in.) thickness of W. Into this tubing is placed highly enriched hollow cylinders of uranium nitride (UN) fuel, the total height of which is about 37.59 cm (14.8 in.). A total of 181 fuel pins make up the stationary core and another 66 fuel pins are located in a series of six cylindrical control drums (11 fuel pins in each). With the fuel in the drums turned full-in, the core is roughly cylindrical in shape and has an effective diameter of about 35.5 cm (14 in.). Each control drum, which is about 14.6 cm (5.75 in.) in diameter and 60.2 cm (23.7 in.) high, also contains a massive TZM reflector which separates the fuel cluster from a T-111 absorber segment. The reference reactor is reflected axially by about 5.08 cm (2 in.) of TZM and radially by an effective 7.62-cm(3-in.) thickness of TZM

Considering end-fittings on fuel pins and including the axial and radial reflectors, the overall height and diameter of the core are both about 55.88 cm (22 in.). The reactor is surrounded by a T-111 pressure vessel. Lithium-7 ($Li^7$) is proposed as the reactor coolant and flows principally in an annular space between the fuel pin and the honeycomb tube.

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## B. SCOPE OF PREVIOUS PROGRAM

Atomics International, under contract to NASA, designed, built, and operated under a previous program a zero-power critical assembly that was a close geometrical mockup of this particular reference design. That experimental program, which is described in detail in Reference 1, consisted of measuring the differential neutron spectra and the changes in critical mass that accompanied the step-wise addition of the various refractory and coolant materials noted above to a basic core that was comprised solely of tantalum (Ta) and fully-enriched uranium (U) metal uniformly distributed throughout the core. Cores containing all of the materials anticipated for use in the reference reactor were also used for determining: (1) the effects of fuel motion in the core; (2) the power distribution; (3) the reactivity worths of a wide variety of absorber, scattering, and structural materials; (4) certain core control characteristics; and (5) a variety of other information, such as neutron lifetime and decay constants, that pertains to dynamic and operating behavior of the reference reactor.

A redistribution of the uranium fuel was carried out for the purpose of achieving a three-zoned, power-flattened core. The resulting configuration was used to measure the new power distribution not only for the case in which all drums were turned to the fuel-full-in position, but also for the case in which the drums were turned to achieve a decrease in K of 1.5%. The critical mass of this power-flattened core was measured for the condition corresponding to all drums in, and for the condition corresponding to four drums in and two drums out. The reactivity changes accompanying the rotation of single drums, two diametrically opposing drums, five drums, and all drums from full-in to full-out were also determined, as was the reactivity control available in all drums with the Ta absorber segments removed.

## C. SCOPE OF PRESENT PROGRAM

The experimental program that is described in this report utilized the same critical assembly and the same experimental techniques as were employed previously, represented an extension of the initial scope of work, and involved investigations of various reactor physics parameters that were closely related to those studied under the previous contract. Specifically, the experimental program involved a measurement of reactivity changes associated with surrounding

the three-zoned, power-flattened core with no less than a 15.24-cm(6-in.)-thick polyethylene shield on sides, top, and bottom. The contribution to the total reactivity change that arose from the upper and lower axial portions of the shield was also measured. In the fully shielded condition, the axial and radial power distributions in a one-twelfth sector of the core were determined in detail and the control characteristics of a single drum as well as all drums ganged were ascertained.

The critical assembly was further reconfigured to achieve a core composition essentially identical to Composition 2 of the previous experimental program. This core contained only Ta (in the form of fuel and honeycomb tubes), $Li_3^7N$, and fuel, and the upper and lower axial reflectors were 10.00 cm (3.94 in.) thick. The solid cylinders of molybdenum (Mo) that make up 55.1% by weight of the upper and lower axial reflectors were then reduced in length from 10.00 cm (3.94 in.) to 4.90 cm (1.93 in.) to 2.45 cm (0.97 in.) and the reactivity changes associated with these two reductions were measured. A power distribution measurement that emphasized the axial distribution was also conducted for the core with the 4.90-cm(1.93-in.)-long reflector segments in place and for the core with the 2.45-cm(0.97-in.) reflectors in place.

Upon restoring the axial reflector segments to nearly full height, the reactivity effects of carrying out a uniform addition of tungsten (W) metal to the core were determined. Initially 29.4 kg of W were added in the form of 0.457-cm (0.180-in.)-diam by 37.53-cm(14.77-in.)-long rods. Subsequently an additional 15.1 kg of W were added in the form of 0.0051-cm(0.002-in.)-thick foil to bring the total W loading to 44.5 kg.

The W metal was then removed from the core and measurements were made to ascertain the reactivity worth of a uniform addition of 9.54 kg of Ta in the form of wire 0.279 cm (0.110 in.) diam by 37.39 cm (14.72 in.) long. This additional Ta brought the total quantity of Ta in the core proper to approximately 59.63 kg.

The core was again returned to the Composition 2 configuration, and a spectrum measurement was conducted by means of a proton-recoil spectrometer. The spherical proton-recoil detector was located, for this measurement, on the axis of the core at the interface of the core and upper axial Mo reflector. The

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distribution of neutrons was measured from about 40 kev to 2.3 Mev, using two-parameter analysis at the lower end of the spectrum.

A version of the reference reactor involving a non-fueled control drum was next investigated on the present program. The volume in each of the six control drums normally occupied by eleven standard fuel elements was filled by powdered $B_4C$ compacted to a density of about 65% theoretical in an aluminum canister. That portion of each of the six drums normally occupied by the massive Ta absorber segment was filled by another aluminum canister into which 0.318-cm (0.125-in.)-thick Mo plates, each about 58.67 cm (23.10 in.) long, were placed. The fuel loading in each of the remaining 181 fuel elements in the stationary part of the core was adjusted to achieve a uniformly loaded critical configuration. The resulting core arrangement was then used to determine the control characteristics of the reactor, first for the rotation of individual drums and then for the rotation of all drums simultaneously. The radial and axial power distributions in this configuration were investigated in detail, not only in the active core but also in the $B_4C$ sector of the control drum.

Finally, the critical assembly was restored to its former fueled-control-drum condition and studies were performed to determine the reactivity effects of adding polyethylene to the core proper. The loading of the 247 fuel elements was made to conform to that previously designated Composition 4A, i.e., the core contained Ta [in the form of fuel and honeycomb tubes, in the form of foil, and in the form of 0.279-cm(0.110-in.)-diam by 37.39-cm(14.72-in.)-long wire], $Li_3{}^7N$, Hf foil, and fuel. A total of 360 polyethylene strips, each triangular in cross section, was inserted in the core in the interstitial positions between honeycomb tubes. The reactivity changes associated with adding these strips generally in groups of 120 were determined. The series of measurements was repeated after two Ta wires each 0.152 cm (0.060 in.) in diameter by 37.47 cm (14.75 in.) long were added to each fuel cluster.

D. PURPOSE OF THE CURRENT WORK

The purpose of both this and the previous program was to conduct a well-defined and accurate series of core physics experiments, the results of which can be used as a fundamental set of benchmarks against which current and future calculational techniques for this type of reactor can be checked.

Since the types, masses, purities, and locations of all materials making up the various compositions were carefully controlled and monitored, a very detailed and accurate geometrical and material representation of the core is available. This situation permits meaningful and detailed comparisons to be made between experimental and analytical data. At the same time, since the critical assembly is a reasonably close geometrical and material mockup of the reference reactor, many control, safety, and operating parameters are more or less directly applicable to an operating reactor. Finally, by systematically adding new materials in a step-wise fashion to a reasonably "clean" assembly (in terms of material composition), the adequacy of various calculational techniques and of the various cross section sets applicable to the reference reactor and other fast reactor systems can also be ascertained.

In addition to the above general purposes, the current work relates to an intercomparison of the control characteristics of the more commonly used poison-reflector type of control drum vis-a-vis the poison-fuel or void-fuel type of control drum that is currently incorporated in the reference design. Also, by surrounding the critical assembly with polyethylene and by adding polyethylene to the core, one can obtain information pertaining to various safety and operating aspects of the reference reactor.

## E. DESCRIPTION OF THE CRITICAL ASSEMBLY

The critical assembly was designed to be a reasonably good geometrical simulation of the reference reactor. An artist's sketch, showing the primary components of the system, is provided in Figure 1. The assembly is composed of a close-packed star-shaped array of 181 fuel elements surrounded radially by 6 massive Mo reflectors. Imbedded in the radial reflector region and also partly in the core region (between the points of the star) are 6 symmetrically located cylindrical control drums whose axes are parallel to the axis of the core. Each control drum contains 11 fuel elements and a molybdenum reflector and is backed by a massive Ta absorber segment. In order to provide a rapid-acting safety mechanism for the reactor, four of the six radial Mo reflector pieces are capable of falling away from the core (scramming) and thereby producing a substantial reduction in reactivity. This scram system consists of two independent

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STATIONARY MOLYBDENUM REFLECTOR (2)

CONTROL DRUM (6)

SIMULATED PRESSURE
VESSEL SEGMENT

SCRAMMABLE MOLYBDENUM
FALL-AWAY REFLECTORS

SAFETY ELEMENT

SAFETY ELEMENT
DRIVE MOTOR

FUEL ELEMENTS

CONTROL DRUM
DRIVE MOTOR (6)

SCRAMMABLE MOLYBDENUM
FALL-AWAY REFLECTORS
CORE STRUCTURE WELDMENT
SAFETY ELEMENT
SAFETY ELEMENT
DRIVE MOTOR

SAMPLE CHANGER
DRIVE MOTOR

DRIVE SCREW (2)

SAMPLE HOLDER TUBE MOUNTING PEDESTAL (6)

SAMPLE CHANGER TABLE

GUIDE POST (2)

7765-4606B

6-24-71 UNCL

Figure 1. Sketch of Critical Assembly

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and diametrically opposed safety elements to each of which are attached two of the Mo reflectors in a ganged fashion.

In the shutdown condition, four reflectors are located away from the core and all six control drums are rotated such that the Ta absorber segment in each drum is in the core region and the drum fuel elements are facing away from the core.

In order to achieve criticality, the four reflectors are raised into position (adjacent to the core) by the safety element drive motors and then the control drums are sequentially "driven in"; i.e., rotated to bring fuel into the core. This drum control system simulates that proposed for the reference reactor.

Surrounding the massive Mo reflectors are four Ta segments which simulate in the radial direction the pressure vessel in the reference reactor. During reactor operation, when the reflectors are in the up-position, the four Ta segments form a cylindrical shell completely enclosing the reactor on the lateral surface.

Dimensionally, the critical assembly is 56.845 cm (22.38 in.) high, including upper and lower axial reflectors, and 57.15 cm (22.5 in.) in diameter, including the massive radial reflectors. The core proper is 37.508 cm (14.767 in.) high and has a "diameter" of 38.33 cm (15.09 in.) as measured from the center-line of one fuel element at a point of the star to the centerline of a diagonally opposite fuel element at the point of the star.

The general features of the reactor in the radial directions can be seen by reference to Figure 2, which represents a cross-sectional view of the reactor at the core midplane. On the external surface, the reactor is surrounded by the Ta segments that simulate the pressure vessel in the reference reactor. One segment is located on each of the two fall-away safety-element systems and one on the outside of each of the two stationary reflectors. The segments have an outside radius of 29.23 cm (11.51 in.), a thickness of 0.691 cm (0.272 in.) and a height of 59.7 cm (23.5 in.). In the operating condition, the Ta segments form a tightly fitting cylindrical shell around the lateral surface of the reactor.

Inside the Ta pressure vessel mockup segments are the massive Mo reflectors. Each of the six reflectors is about 60.2 cm (23.7 in.) high and has an outside radius of 28.60 cm (11.26 in.). The thickness from the outer radius to the
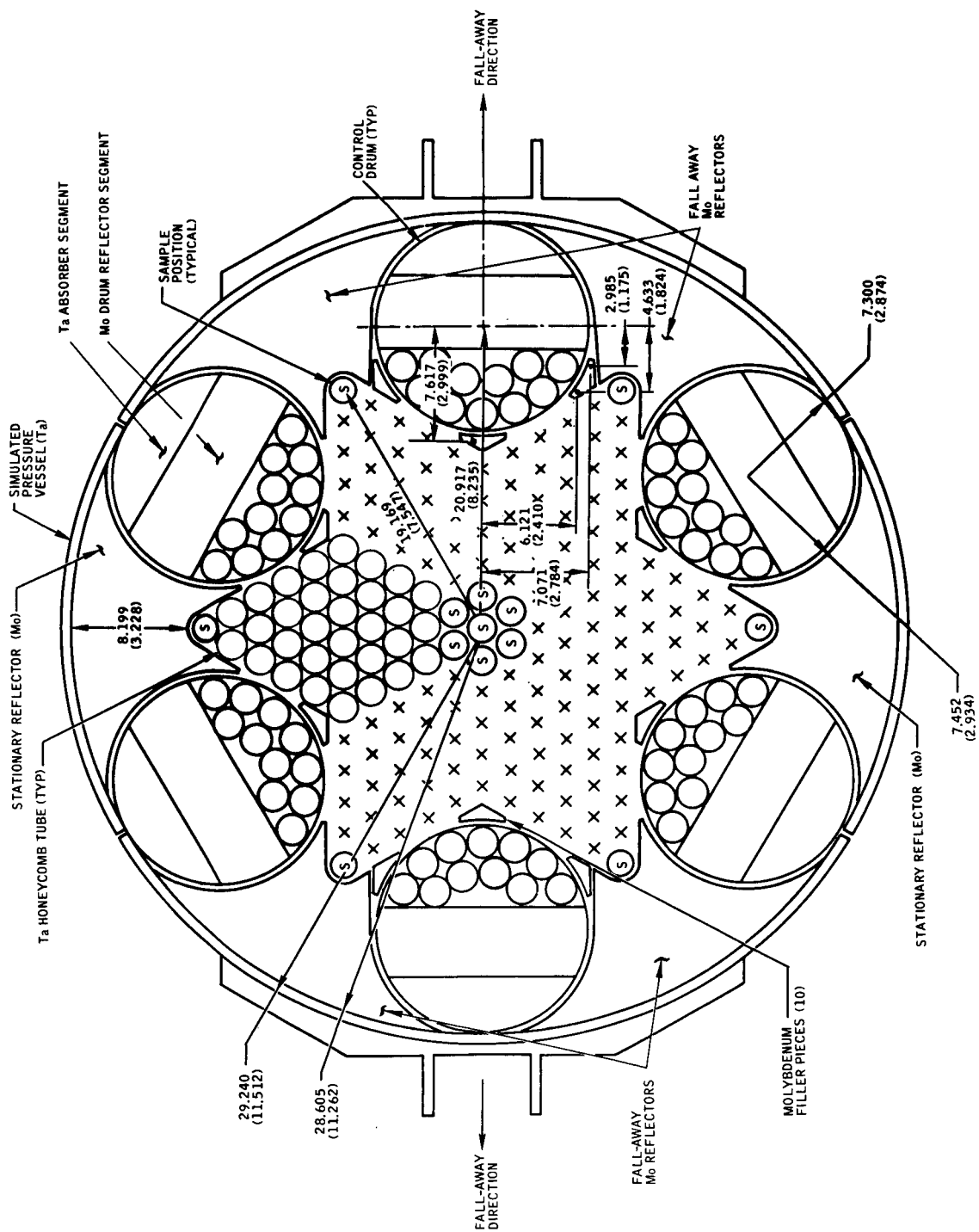
Figure 2. Cross Sectional View of the Critical Assembly at the Core Midplane

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7765-4668A

nearest fuel element is 8.20 cm (3.23 in.). The reflectors have circular cutouts for accommodating the rotatable control drums and therefore wrap around the drums to some extent. However, in order to allow four of the reflectors to fall away from the core, a portion of these four reflectors has been cut away so that they "clear" the drums. Four small triangular Mo filler pieces are therefore installed in the stationary core in such a way that, when all reflectors are in the up-position, they are, for all practical purposes identical.

Located within the region occupied by these massive Mo reflectors and the six control drums is the star-shaped stationary core. The small circles shown in Figure 2 represent some of the 181 Ta honeycomb tubes that simulate the primary core structural member in the reference core. The location of the center line of the remainder of the core elements are shown by an "X" in the figure. The honeycomb tubes are 59.941 cm (23.599 in.) high, are 2.159 cm (0.850 in.) in outside diameter, have a 0.0254-cm(0.010-in.) wall, and are located on a 2.215-cm(0.872-in.) lattice pitch. In order to conduct certain experiments, the standard elements marked in the figure with the letter "S" can be removed and replaced by a special fuel element. The central seven were used during this program for inserting a spherical proton-recoil detector along the axis of the core.

Six additional triangular-shaped Mo pieces, apart from the four noted above, are placed in the core to fill up the void space that exists between the hexagonal array of honeycomb tubes and the control drums. A cross sectional view of the core as produced by a vertical section formed by passing a plane through the axis of the core and the axis of a control drum is shown in the right-hand half of the centerline of the drawing of Figure 3. The left half of the figure is the view that would be seen along a section formed by passing a plane through the axis of a fuel element at the point of the star. To provide an indication of the relative positions of the fuel element components to the other core components, an outline of one fuel element is depicted in the figure.

The axis of each of the six control drums is parallel to the axis of the core and located on a 20.917-cm(8.235-in.) radius. Each drum controls about $2 in reactivity but is not used for rapid shutdown since its speed of rotation, both for the case in which fuel is going into the core and the case in which fuel is going out, is low (about 0.12 revolution per minute). The detailed layout of the

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UPPER GRID PLATE
CONTROL DRUM

TANTALUM PRESSURE VESSEL
MOCKUP SEGMENT

TRIANGULAR MOLYBDENUM
FILLER PIECE

SCRAMMABLE REFLECTOR
MOUNTING BRACKET

TANTALUM ABSORBER

MOLYBDENUM REFLECTOR

DRUM FUEL ELEMENT

LOWER GRID PLATE OF
CONTROL DRUM

LOWER DRUM BEARING

PIVOT POINT FOR
SCRAMMABLE REFLECTORS

UPPER CORE
GRID PLATE

FUEL CLUSTER

U₂³⁷N

SOLID MOLYBDENUM AXIAL
REFLECTOR

ECCENTRIC
MOLYBDENUM AXIAL
REFLECTOR

LOWER CORE GRID PLATE

SAMPLE HOLDER TUBES

CORE STRUCTURE WELDMENT

TANTALUM PRESSURE VESSEL
MOCKUP SEGMENT

MASSIVE MOLYBDENUM
RADIAL REFLECTOR

CORE STRUCTURE
WELDMENT

10.69
(3.84)

37.49
(14.76)

10.009
(3.94)

60.139
(23.677)

7765-4617A

a. Vertical Plane Passing Through the Axis
   of the Core and the Axis of the Fuel
   Element at a Point of the Star

b. Vertical Plane Passing Through the Axis of
   the Core and the Axis of a Drum

Figure 3.   Cross Sectional View of the Critical Assembly in the Vertical Direction

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control drum is shown in cross sectional view at the drum midplane in Figure 4. The main structural member of the drum is the massive Mo reflector piece to which an upper and lower drum grid plate are attached. This Mo piece is 60.2 cm (23.7 in.) high (the effective height of the control drum). Each drum normally has a Ta absorber segment which is also 60.2 cm (23.7 in.) high. In one series of experiments reported herein, this segment was removed and replaced by an aluminum canister having approximately the same external dimensions and containing Mo plates. This canister is shown in Figure 5.

On the opposite side of the drum is a region which normally contains a group of honeycomb tubes identical to those in the stationary portion of the core. Since the void fraction in this region would be rather high with honeycomb tubes alone, several round Mo filler rods are inserted. All of these rods are 60.2 cm (23.7 in.) high, but vary in diameter, as indicated in the figure. In addition to the round rods, a large trapezoidal-shaped filler piece 60.2 cm (23.7 in.) high, is also utilized to fill the gap between the Mo reflector segment and the inner ring of honeycomb tubes. In the series of experiments in which the Ta absorber segment is replaced by an aluminum canister filled with Mo plates, the drum fuel elements were removed and replaced by another aluminum canister as also depicted in Figure 5. This canister, which is somewhat larger in size, was filled with $B_4C$ powder.

Within each Ta honeycomb tube is located eccentrically a Ta fuel tube which is used to contain the uranium fuel. This tube (see Figure 6) is 58.09 cm (22.87 in.) long, has an outside diameter of 1.575 cm (0.620 in.) and a wall thickness of 0.0254 cm (0.010 in.). Its centerline is offset from the centerline of the honeycomb tube by 0.0508 cm (0.020 in.). This eccentricity is established and maintained by an eccentric Mo reflector piece, 2.09 cm (0.823 in.) in outside diameter, 1.595 cm (0.628 in.) in inside diameter, and 10.00 cm (3.94 in.) long, one of which is located on each end of the element. In order to form a more or less continuous axial reflector, a solid Mo cylindrical reflector is also placed at each end of the element and within the fuel tube. The latter reflectors are 1.493 cm (0.588 in.) in diameter and are also 10.00 cm (3.94 in.) long. Between the solid, axial, Mo reflector cylinders is located the uranium fuel, which consists of a cluster of uranium metal rods, each 0.432 cm (0.170 in.) in diameter,
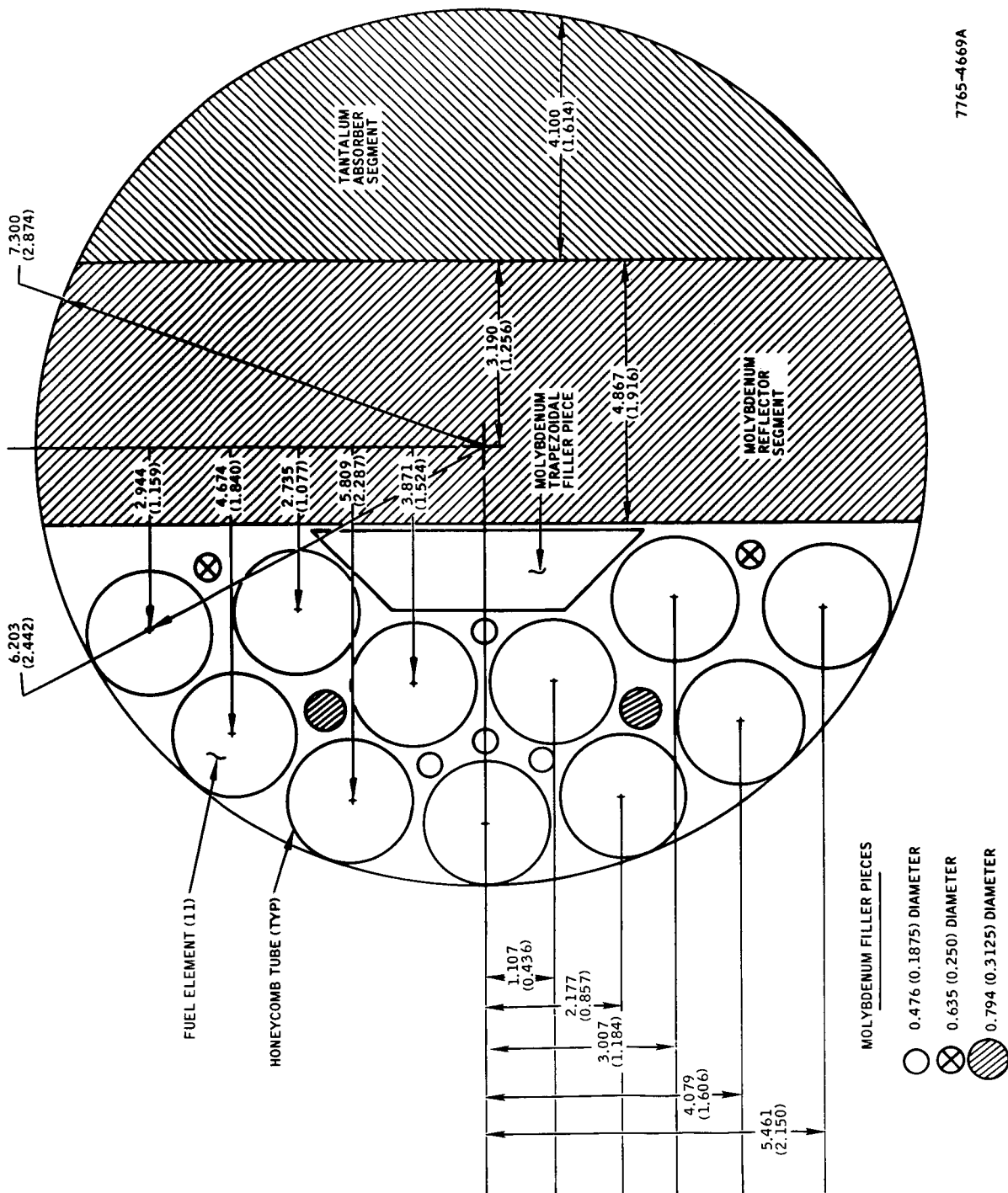
Figure 4. Cross Sectional View of the Control Drum at the Core Midplane

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REAR PLATE 0.635 cm (0.250 in.)

ALUMINUM CANISTER
CONTAINING
MOLYBDENUM PLATES

ALUMINUM CANISTER
CONTAINING BORON
CARBIDE COMPACTED
POWDER

60.122 cm
(23.670 in.)

59.995 cm
(23.620 in.)

MOLYBDENUM
PLATES

COVER PLATE
0.792 cm (0.312 in.)
THICK

MOUNTING
HOLE (2)

COVER PLATE
0.792 cm
(0.312 in.) THICK

ALIGNMENT PINS

0.157 cm (0.062 in.)
MAX R (TYP)

4.100 cm
(1.614 in.)

0.157 cm (0.062 in.)
MAX R (TYP)
ALUMINUM

5.62 cm
(2.214 in.)

7.300 cm
(2.874 in.) R

7.300 cm
(2.874 in.) R

6526-5504B

Figure 5.   Aluminum Canisters for B$_4$C-Controlled Reactor

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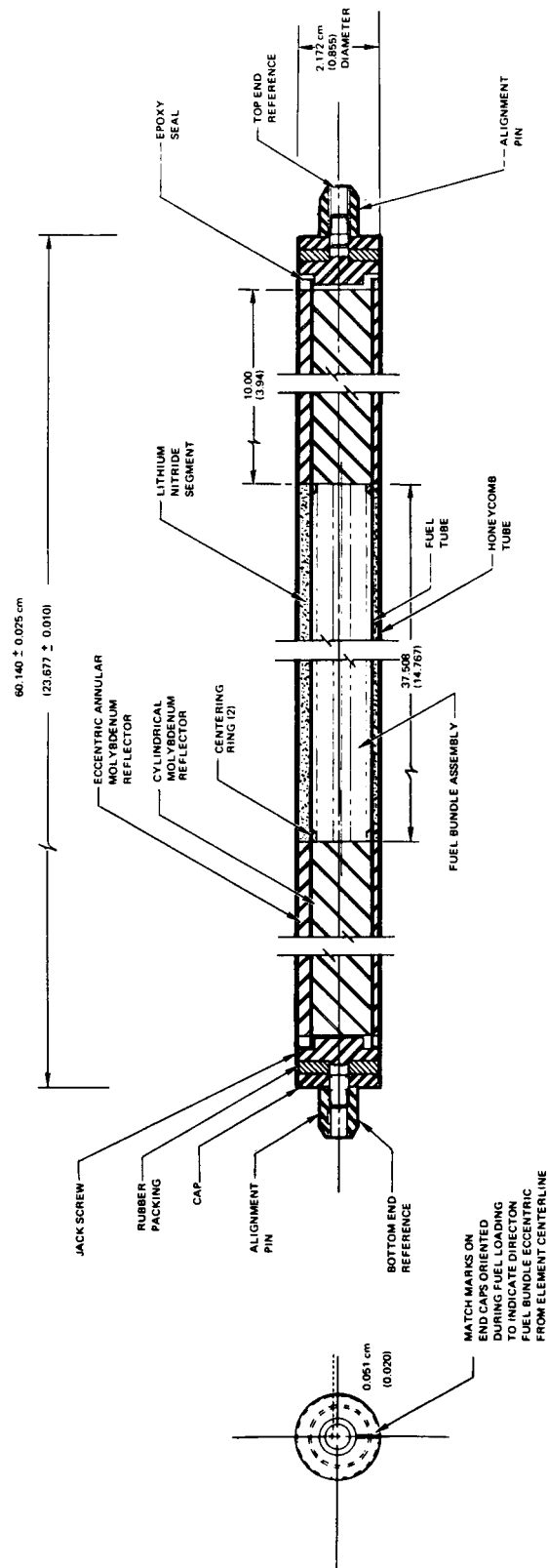
Figure 6. Critical Assembly Fuel Element

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the number of rods in each cluster normally varying from six to seven depending upon the particular experiment. A typical 7-rod cluster is shown in Figure 7. Each rod of fuel in the fuel cluster is made up of two shorter rods, one 15.24 cm (6 in.) long and one 22.268 cm (8.767 in.) long, placed end to end to make a total length of 37.508 cm (14.767 in.), the height of the active core. In order to make the fuel cluster more stable dimensionally, the 15.24-cm (6-in.) and 22.268-cm (8.767-in.) lengths are stacked alternately so that there are actually two parting planes. In addition, a Ta centering ring, whose inside diameter corresponds to the circle circumscribing the fuel cluster, 1.295 cm (0.510 in.), is placed at the top and bottom of the cluster. To provide further rigidity to the fuel bundle, a two-turn or three-turn wire wrap of Mo is utilized, in some cases, at various positions along the height of the cluster.

Since, in some core configurations, more fuel than is contained in a 7-rod cluster of rods is required for criticality, some additional types of uranium were needed. Also, inasmuch as very fine and uniform fuel adjustments were needed for certain experiments, a smaller subdivision than that consisting of single rods was needed. These two requirements were met by swaging some of the uranium metal rods into wire, one of which was 0.152 cm (0.060 in.) in diameter by 37.465 cm (14.75 in.) long and the other 0.066 cm (0.026 in.) in diameter by 37.465 cm (14.75 in.) long. The 0.152-cm(0.060-in.)-diam wire was designed for insertion into the cusp spaces around the outer periphery of the fuel cluster, whereas the 0.066-cm(0.026-in.)-diam wire was inserted into the triflute spaces on the inside of the cluster as shown in Figure 7. Since 15.24-cm (6-in.) and 22.225-cm (8.767-in.) lengths of fuel rods are never used separately in a standard fuel cluster (i.e., they are always placed end-to-end), the term rod is used in this report to designate a column 0.432 cm (0.170 in.) in diameter by 37.508 cm (14.767 in.) long.

The long and short uranium fuel rods were enriched to 93.197 and 93.149%, respectively, in the $U^{235}$ isotope and, as has already been noted, were of a metallic form.* The uranium wires were also enriched to 93.197% in the $U^{235}$ isotope. Since the reference core is designed to use UN fuel, a suitable method

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*In order to reduce contamination that would result from frequent handling of bare uranium metal, all fuel was coated with a thin layer of nonhydrogenous plastic paint.

U235

Li₃⁷N

TWO TURN
WIRE WRAP

HAFNIUM FOIL

TANTALUM FOIL

TUNGSTEN FOIL

FUEL TUBE (Ta)

HONEYCOMB TUBE (Ta)
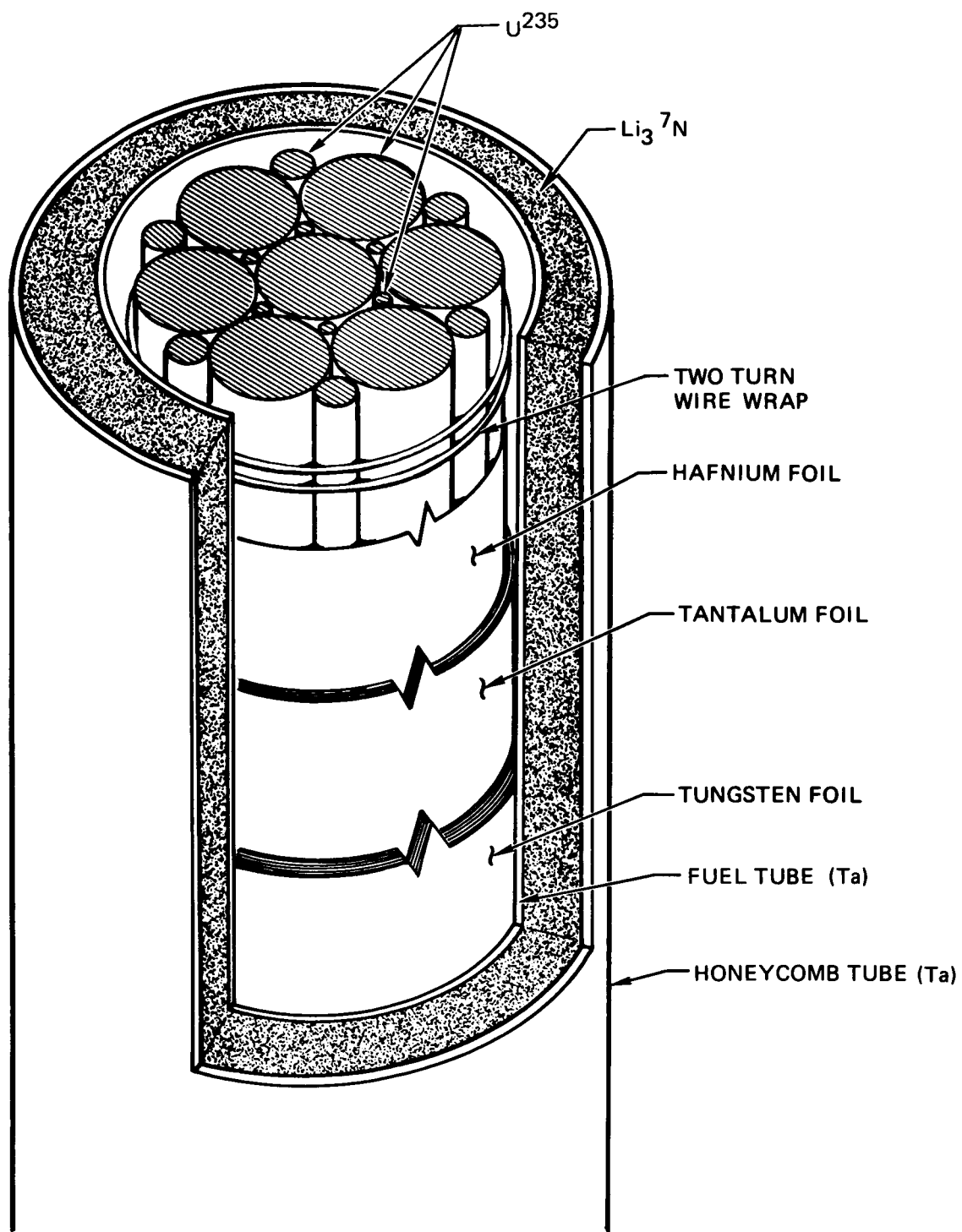
6-24-71            7765-4609A

Figure 7. Cutaway View of the Central Region of the Fuel Element

for incorporating the element nitrogen was required. This requirement was satisfied by the use of $Li_3^7N$, a ceramic-like material that would also satisfy the need for a simulation of the lithium-7 coolant proposed for the reference reactor. This $Li_3^7N$ material was fabricated into a free-standing body with a clam-shell form and was inserted in the annular space between the fuel tube and the honeycomb tube. Since this space does not have a uniform gap width because of the eccentricity in the location of the Ta tubes, the $Li_3^7N$ had a corresponding nonuniform wall thickness. It had, nominally, an inside diameter of 1.600 cm (0.630 in.) and outside diameter of 2.078 cm (0.818 in.) and a length of 37.34 cm (14.70 in.). It is thus confined only to the core proper.

Whereas the fuel and honeycomb tubes are pure Ta in the critical assembly, the reference reactor calls for T-111 tubing for these components. Also, the specifications for the reference reactor call for a very heavy-walled fuel tube with a W liner. T-111 is an alloy of Ta containing 8.5 wt % W and 2.3 wt % Hf. In order to provide these two additional materials (W and Hf), as well as additional Ta, metallic foils of these elements were coiled and inserted into the fuel tube around the fuel cluster in the manner depicted in Figure 7. Since additional W material was required for certain experiments, a W rod 0.457 cm (0.180 in.) in diameter by 15.24 cm (6.00 in.) long, weighing, on the average, 48.313 gm, and a W rod 0.457 cm (0.180 in.) in diameter by 22.28 cm (8.77 in.) long, weighing, on the average, 70.752 gm, were placed end-to-end in the center of a six-rod fuel cluster. The total mass of W available in this form amounted to 29.408 kg.

Even with the additional Ta foil in the critical assembly, the total mass of this material was still less than that contemplated for the reference reactor; consequently, another method for further increasing the total Ta loading was devised for specific experiments. This method consisted of inserting a 0.279-cm(0.110-in.)-diam by 37.39-cm(14.7-in.)-long Ta wire into the center of the fuel cluster when it consisted of less than 7 rods and/or adding a 0.152-cm (0.060-in.)-diam by 37.39-cm(14.7-in.)-long Ta wire in the place of a uranium wire of the same diameter. Also, a 0.356-cm(0.140-in.)-diam by 59.69-cm (23.5-in.)-long Ta wire was, on occasion, inserted into the triflute spaces between honeycomb tubes in the stationary part of the core. A total of 300 such spaces, which are totally surrounded by honeycomb tubes, was available for this purpose.
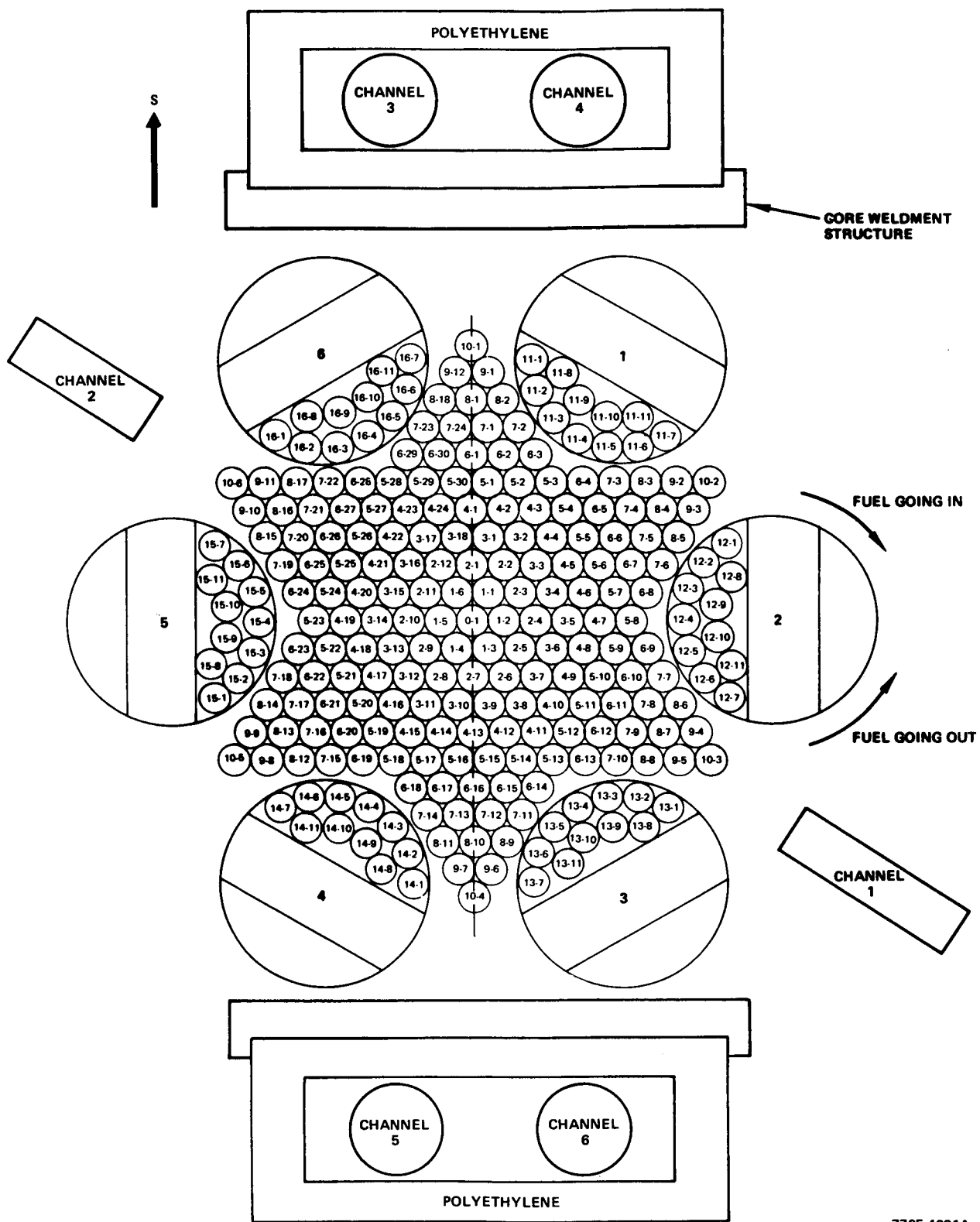
Figure 8. Core Map and Neutron Detector Locations

7765-4631A

Since $Li_3{}^7N$ reacts with moisture in the air to form ammonia, among other products, the annular region between the honeycomb tube and the fuel tubes had to be hermetically sealed. An epoxy cement was used for this purpose and was confined to the annular gap in the region outside of the reflectors, as can be seen in Figure 6. Thus, the internal volume of the fuel tube remained accessible for purposes of fuel and material adjustments once the seal was made on the $Li_3{}^7N$.

To maintain the fuel cluster and other components in the proper position in the fuel tube, an aluminum end-plug was inserted into each end of the honeycomb tube. This plug also served to align the fuel elements (the term used here to designate the combined fuel and honeycomb tubes) in an upper and lower grid plate. By tightening the alignment pin seen in Figure 6, the rubber packing expanded out and made a reliable mechanical seal on the honeycomb tube.

A total of 181 of these fuel elements made up the stationary core and an additional 66 identical elements, 11 in each of 6 drums, were used in the movable drums to bring the total to 247 fuel elements.

The design of the fuel element was such that each fuel tube was located eccentrically within each honeycomb tube. This feature was used, during the previous program, to measure the reactivity effects resulting from fuel displacement. For all experiments described in this report, the fuel elements were turned in such a way that the fuel tube eccentricity in each fuel element was perpendicular to the core radius.

Additional details, particularly with regard to masses of individual core components, instrumentation, and special features of the critical assembly can be obtained from Section II and Appendix C of Reference 1.

Throughout an experimental program of this type, it is necessary to have a means for identifying and locating individual fuel elements and the relative locations of control drums. The method used for this critical assembly is shown in Figure 8 along with an indication of the location of neutron detectors. The fuel element identification scheme consisted of assigning the designation 0-1 to the center fuel element location, 1-1 through 1-6 to the first ring of locations, 2-1 through 2-12 to the second ring of locations, and so forth. Drum fuel elements are assigned designations in the 11 to 16 range so that the second digit designates the drum number. For example, 13-1 is a fuel element location in Drum 3.

## F. EXPERIMENTAL TECHNIQUES

The basic technical methods for measuring reactivity, critical mass, power distributions, neutron spectra, etc. are identical to those employed previously on this program (see Section III of Reference 1). For the sake of completeness, the techniques will be briefly outlined here.

### 1. The Measurement of Reactivity

#### a. Inverse Kinetics Technique

The fundamental method for measuring reactivity during this experimental program was that designated inverse kinetics or reactivity vs time. The method has been employed for several years at Atomics International primarily in the work being conducted at the Epithermal Critical Experiments Laboratory (ECEL) split table critical assembly where the technique, which had been previously used irregularly by other laboratories, was coded and put to routine use. The basic principles are described in Reference 2. Since the initiation of its routine use at the ECEL in 1960, it has been further improved, particularly in the area of the inclusion of the effects of a constant neutron source.[3] It is now utilized in a routine manner at several other laboratories, including Argonne National Laboratory and at Karlsruhe, Germany.

The name "inverse kinetics" is based on the fact that, whereas one normally assumes that a known reactivity change is made and subsequently calculates the change in the neutron population with time, in this technique the change in the neutron population is measured directly by the neutron detector and from this information the reactivity is derived. The fundamental equation is

$$\frac{1}{\beta_e}\frac{\Delta k_e}{k_e} + \frac{\ell}{\beta_e k_e}\frac{S_e}{n} = 1 + \frac{1}{nk_e}\left[\frac{\ell}{\beta_e}\frac{dn}{dt} - \sum a_i e^{-\lambda_i t}\left(n_o + \lambda_i \int_0^t k_e n e^{\lambda_i t}\,dt\right)\right] \quad,$$

where

$k_e$ = effective multiplication constant

$\Delta k_e = k_e - 1$

$\ell$ = neutron lifetime (sec)

$\beta_e^i$ = effective delayed neutron fraction for the i$^{th}$ group

$\beta_e$ = effective delayed neutron fraction, $\sum \beta_e^i$

n = number of neutrons in the reactor

t = time (sec)

$\lambda_i$ = decay constant for i$^{th}$ precursor group (sec$^{-1}$)

$S_e$ = effective source strength (n/sec)

$n_o$ = equilibrium neutron population.

If the output of one of the neutron detectors in the assembly is fed to a multi-channel analyzer operating in the time mode, the change in the neutron population as a function of time is directly measured. From this power trace, the change in population with time, dn/dt, can also readily be extracted, Since the constant source term is, in most cases, virtually negligible in this assembly, and $\ell$ and $\beta_e$ can be calculated with a reasonable degree of accuracy, the reactivity as a function of time can be derived. It can be shown, however, that the reactivity is very insensitive to values of $\ell$ and $\beta_e$; consequently, large errors in the calculated values of these quantities result in negligible errors in the results. Thus, only the term in the summation contributes substantially to the measured reactivity worth. Since $\beta_e$ occurs within the summation sign as a ratio with $\beta_e^i$, the actual parameter of interest there is $a_i$, a quantity that is equal to $\beta_e^i/\beta_e$ and that is well known.

b. Inverse-Counting Technique

A second method for measuring reactivity — in particular, large negative reactivities — was based upon inverse counting techniques. In this technique, a $Cf^{252}$ source ($\sim 2 \times 10^6$ n/sec) was placed in the center of the reactor. The neutron detectors were used to measure the neutron population over some pre-selected time interval as a function of various subcritical reactor configurations. Alternatively, the steady-state current achieved in a current detector was recorded. By making measurements at or very near a configuration where the reactivity is known indirectly by inverse-kinetics measurements, the method is normalized and then used to derive the reactivity for some unknown conditions. The conversion of the counting data to reactivity is derived as follows:

By definition,
$$\frac{1}{M} = 1 - k \quad .$$

Since C, the total counts for some fixed time interval, is directly proportional to M, one can write that

$$C = \epsilon M \quad .$$

Therefore,
$$\frac{\epsilon}{C} = 1 - k \quad .$$

For some known normalization reactivity value, $k_n$,

$$\frac{\epsilon}{C_n} = 1 - k_n \quad .$$

Therefore, by taking the ratio,

$$\frac{C_n}{C} = \frac{1 - k}{1 - k_n} \quad .$$

Since,
$$k = -\frac{1}{\frac{\beta}{\rho} - 1} \quad ,$$

where $\rho$ = reactivity in dollars, one can eliminate k and solve for reactivity in dollars. Thus, the reactivity, in terms of the ratio of the counts, C, at some unknown reactivity to the counts, $C_n$, at some normalization value, is

$$\rho = -\frac{\left(\frac{C_n}{C}\right)\rho_n}{\beta_{\rho_n}\left[1 - \left(\frac{C_n}{C}\right)\right] - 1} \quad ,$$

where $\rho_n$ is the known normalization reactivity in dollars. The value for $\beta$ is calculated, the value for $\rho_n$ is determined by inverse kinetics measurement at a close to critical, and, since the quantity $C_n/C$ is measured, the reactivity can be obtained.

c.   Drum Worth Technique

A third type of reactivity determination that was used during the experimental program involved, for both positive and negative values, changes in the position of a calibrated control drum. This method is a secondary technique since

the drum itself is calibrated initially by the inverse-kinetics technique. It is, however, a very convenient and rapid method for ascertaining the magnitude of reactivity changes within a few cents.

Typically, the drum position is noted at which a base reactor configuration or composition is just critical. From a drum-worth curve, the total excess reactivity is determined. A change, such as the substitution of a fuel-loaded fuel element for an empty one or the addition of Ta wires to the core, is made and a new critical position for the calibrated drum is noted. This new position yields a new total excess reactivity value which, when algebraically subtracted from the former one, yields the reactivity change caused by the operation.

## 2. The Measurement of Drum Worth

As noted above, the inverse kinetics technique was utilized in establishing the reactivity worth of single control drums, and it was applied through one or both of two methods. In a so-called "continuous drive" method, the reactor was brought to critical, allowed to stabilize, and then the drum was driven from the full-in to the full-out position. The ensuing power trace was analyzed by the inverse kinetics technique in order to derive the worth of the drum as a function of time. From the known drive speed, the worth was then established as a function of position. This continuous drive method was employed in order to evaluate the worth of a single drum where detailed information on the shape of the worth curve at or near the full-in position was particularly important.

A so-called "step-wise" method for obtaining the worth of single drums was utilized where greater precision was required at or near the full-out position. The step-wise method involved only small reactivity changes; consequently, the validity of the results was less subject to error. In this technique, Drum No. 6, for example, is placed with fuel full-in and the diametrically opposite drum (No. 3 in this case) is banked out such that, with all other drums full-in, the reactor is critical. After a period of time is allowed at level power, data collection is initiated. Drum No. 6 is then turned out a few degrees and maintained at that position for about one minute. Drum No. 3 is then turned in by an amount that not only offsets the small negative reactivity produced by Drum No.6, but also provides a small amount of excess. Again, all drums remain stationary for about 1 minute, whereupon Drum No. 6 is turned out a few degrees more.

Drum No. 3 is then moved in, and the process is repeated in this step-wise fashion, the worth of Drum No. 6 being measured as it is stepped out and the worth of Drum No. 3 as it is stepped in. The integral worths are established by algebraically summing the step-wise reactivity values.

3.   The Measurement of the All-Drums-In Excess Reactivity

The measurement of the all-drums-in excess reactivity was accomplished in most cases by noting the position of one or more drums when the reactor was just critical for several minutes. The previously established drum worth curve was then used to determine the excess reactivity that would be obtained if the drum or drums were turned to the full-in position. In some cases, where the total excess reactivity is sufficiently small, the all-drums-in excess reactivity was determined directly by actually driving all drums full-in and analyzing the power rise by the inverse kinetics (positive period) technique.

4.   The Measurement of Critical Mass

The values for the critical mass of the various core compositions were based upon the all-drums-in excess reactivity value and upon the core-averaged worth of fuel. The latter quantity was determined by noting the change in the all-drums-in excess reactivity that occurred upon removal of uranium fuel from the core in a uniform manner. In some cases, the latter quantity was assumed to be known from measurements conducted under one or more of the previous contract tasks.

5.   The Measurement of Power Distribution

The power distribution in the various core compositions and/or configurations of this program was measured by inserting previously unirradiated uranium wire (0.066 cm in diameter) into the fuel cluster in each fuel element making up a one-twelfth sector of the core. The wires were irradiated at a power level of about 40 watts for a period of about one hour, at the end of which time the reactor was scrammed and the wires removed. Wire segments, nominally 1.27 cm (0.5 in.) long, were cut from the full-length wires at various positions along their length, or, in some instances, the entire wire was cut into the nominally 1.27 cm (0.5 in.) lengths. These wire segments were weighed to an accuracy of ±0.1 mg.

The wire segments were counted in several gamma channels beginning a few hours after reactor shutdown. Standard NaI scintillation detectors were used, with the amplifiers set for integral counting of gamma rays with energies above 0.5 Mev. In order to establish a decay function, a separate counting of one of the most active wire segments was conducted in one of the standard NaI detectors used in the routine counting process. A least-squares fit of the data from this monitor wire was used for decay correction. All channels were controlled by the same time base and dual preset counter. Fifteen-minute counting intervals were generally used, and some wire segments were counted more than once. The channels were normalized to one another by counting a group of several wires in all channels and comparing the resulting decay-corrected counts.

A computer code was used to correct the data for decay, background, mass normalization (after subtracting the weight of the Kel-F) and counter normalization. The resulting relative activities, which are directly proportional to power, were then plotted as a function of radial and axial position. The errors due to counting statistics only are estimated to vary from 1/2 to 1-1/2%. The mass determination is expected to introduce an error of approximately ±0.2% and there is an uncertainty of about +0.025 cm (0.01 in.) in the axial position of a wire within the fuel element.

6. The Measurement of the Neutron Spectrum

The differential neutron spectrum was measured over the energy range from 50 kev to 2.3 Mev by means of the proton-recoil spectrometer, an instrument that has been under development and test for several years.[4-8] The spectrum measurements utilized a group of six gas-filled spherical-type detectors as developed by P. W. Benjamin, et al. The spheres are 3.94 cm (1.55 in.) inside diameter and have a 0.058-cm(0.023-in.)-wall thickness. The central anode consists of 0.00254-cm(0.001-in.)-diam tungsten wire. Each of the detectors in the group has a different filling of hydrogen and/or methane gas along with a small amount of nitrogen or helium-3 for energy calibration. The unfolding of the proton-recoil spectrum was based upon the techniques developed by P. W. Benjamin, et al, and upon corrections presented recently at an IAEA Conference.[9] Two-parameter analysis was utilized below about 120 kev in order to discriminate against gamma-ray induced events.

## G. UNITS OF MEASURE

All of the reactor component were designed, built, and checked to physical dimensions in inches. Consequently, the International System of Units used here for the unit of length is derived from the latter data. The masses quoted herein for fuel and other reactor materials were, however, measured directly in grams. The proton-recoil spectrometer detectors were filled by an outside vendor to specified pressures expressed in atmospheres. For reporting purposes, these units were converted to newtons/square meter. All other physical units of measurement, unless otherwise noted in the text, were based directly upon the units quoted.

## II. EXPERIMENTAL RESULTS

### A.  SUMMARY OF RESULTS

#### 1.  Core Material Masses

The masses of the materials making up the basic core structure remained, for the most part, unchanged throughout the experimental program.  A tabulation of these basic material masses is given in Table 1.  For all cores, except 5.0 and 5.1, the masses of materials shown in Column 5 should be assumed to be present at all times.  Thus, most of the experimental program involved the addition of a different form of the same material or different materials to this basic structure in accordance with the data shown in Columns 4 through 12 of Table 2.  Cores 5.0 and 5.1, which pertain to the $B_4C$-controlled reactor, involved removal of eleven fuel elements, several Mo filler pieces, and one Ta absorber segment from each of six drums.  These items were replaced, respectively by one $B_4C$-filled and one Mo-filled aluminum canister in each drum. The removal of these items and the subsequent replacement altered the total number and therefore masses of certain core materials.  These changes are reflected in the data of Column 6 of Table 1.  The total masses of each material making up any given core can therefore be derived from the tabulations contained in Table 1, Columns 5 and 6, and in Table 2, Columns 5 through 13.

#### 2.  Core Data

Table 2 presents a detailed listing of all of the major reactor configurations that were constructed during this program.  The core numbering system, as shown in Column 2, was set up to correlate with certain functions or experimental investigations that were undertaken as described in Column 1.  Cores 1.0 through 1.2, for example, pertain to studies of the reactivity effects that accompany the addition of a polyethylene shield around a 3-zoned, power-flattened core.  Cores 2.0 and 2.1 were used to determine the reactivity effects of adding Ta wire to the system, and, with a slight alteration of fuel in the central seven elements, Core 2.0 was used to investigate the neutron spectrum at the boundary of the core and upper reflector.  In like manner the 3rd, 4th, 5th, and 6th series of cores were associated with, respectively, axial reflector worths, tungsten worths, a $B_4C$-controlled reactor, and, finally, the reactivity changes that accompany the addition of polyethylene to the core proper.

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## TABLE 1

## MASSES OF MATERIALS IN VARIOUS CORES

| Type of Material | Description | Number of Pieces | | Mass of All Pieces (kg) | |
|---|---|---|---|---|---|
| | | All Cores Except 5.0 and 5.1 | Cores 5.0 and 5.1 | All Cores Except 5.0 and 5.1 | Cores 5.0 and 5.1 |
| Ta | Fuel Tubes | 247 | 181 | 32.41* | 23.75* |
| Ta | Honeycomb Tubes | 247 | 181 | 44.89† | 32.86† |
| $Li_3^7N$ | Segments | 247 | 181 | 10.13 | 7.42 |
| Mo | Axial Reflector Eccentric Cylinder | 494 | 362 | 71.94 | 52.72 |
| Mo | Radial Reflectors | 6 | 6 | 399.28 | 399.28 |
| Mo | Drum Reflectors | 6 | 6 | 246.88 | 246.88 |
| Mo | Core Filler Segments | 10 | 10 | 11.28 | 11.28 |
| Mo | Drum Filler Segments | 6 | 0 | 16.55 | 0 |
| Mo | Drum Filler Rods | 48 | 0 | 8.59 | 0 |
| Ta | Pressure Vessel | 1 | 1 | 120.31 | 120.31 |
| Ta | Drum Absorber Segments | 6 | 0 | 230.63 | 0 |
| $B_4C$ | Powder in Canister in Drum | 0 | - | 0 | 32.21 |
| Mo | Plates in Canister in Drum | 0 | 66 | 0 | 107.96 |
| Al | Canisters for Mo Plates | 0 | 6 | 0 | 5.074 |
| Al | Canisters for $B_4C$ Power | 0 | 6 | 0 | 6.333 |

*64.6% by weight (20.94 and 15.34 kg) in core proper
†62.6% by weight (28.07 and 20.57 kg) in core proper

## TABLE 2

## SUMMARY OF CORE DATA

| Functional Description | Core Number | Rods | Wires | Fuel Loading (kg) | Polyethylene Around Core | Polyethylene Strips | Ta Wire, 0.279 cm diam | Ta Wire, 0.152 cm diam | Ta Foil, 0.0128 cm Thick | W Foil and Rod | Hf, 0.008 cm Thick | Solid Mo Reflector Top | Solid Mo Reflector Bottom | Total Mo Axial Reflector Top | Total Mo Axial Reflector Bottom | Measured System Excess Reactivity* (¢) | Corrected System Excess Reactivity† (¢) | Critical Mass (¢) | Conversion (Factor) (¢/kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Polyethylene Worth, Power-Flattened Core | 1.0§ | 6 | 1 | 175.0124 | 0 | 0 | 0 | 0 | 21.70 | 15.15 | 4.12 | 44.20 | 44.20 | 80.17 | 80.17 | 44.6 | 30.6 | - | - |
| | 1.1§ | 7 | 0 | 175.0124 | 352.667 | 0 | 0 | 0 | 21.70 | 15.15 | 4.12 | 44.20 | 44.20 | 80.17 | 80.17 | 136.7 | 136.7 | - | - |
| | 1.2§ | 7 | 4 | 175.0124 | 242.083 | 0 | 0 | 0 | 21.70 | 15.15 | 4.12 | 44.20 | 44.20 | 80.17 | 80.17 | 121.1 | 121.1 | - | - |
| Ta Worth and Neutron Spectrum | 2.0 | 6 | 7 | 174.8833 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 44.20 | 44.20 | 80.17 | 80.17 | 182.5 | 168.5 | 171.55 | 50.6 |
| | 2.1 | 6 | 7 | 174.8833 | 0 | 0 | 9.54 | 0 | 0 | 0 | 0 | 44.20 | 44.20 | 80.17 | 80.17 | 163.5 | 149.5 | 171.93 | 50.6 |
| Axial Reflector Worth | 3.0 | 6 | 7 | 174.8833 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 44.20 | 43.11 | 80.17 | 79.08 | 174.1 | 160.1 | 171.72 | 50.6 |
| | 3.1 | 6 | 7 | 174.8833 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21.56 | 21.55 | 57.53 | 57.52 | 25.7 | 11.7 | 174.65 | 50.6 |
| | 3.2 | 7 | 0 | 177.20791 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 21.56 | 21.55 | 57.53 | 57.52 | 165.2 | 151.2 | 174.69 | 60.0 |
| | 3.3 | 7 | 0 | 177.20791 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10.78 | 10.78 | 46.75 | 46.75 | 33.8 | 19.8 | 176.88 | 60.0 |
| W Worth | 4.0 | 6 | 6 | 171.86181 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 44.20 | 43.11 | 80.17 | 79.08 | 23.5 | 9.5 | 171.67 | 50.6 |
| | 4.1 | 6 | 6 | 171.86181 | 0 | 0 | 0 | 0 | 0 | 29.409 | 0 | 44.20 | 43.11 | 80.17 | 79.08 | 95.1 | 81.1 | - | - |
| | 4.2 | 6 | 6 | 171.86181 | 0 | 0 | 0 | 0 | 0 | 44.539 | 0 | 44.20 | 43.11 | 80.17 | 79.08 | 145.9 | 131.9 | 169.51 | 56.2 |
| | 4.3 | 6 | 5.5 | 170.25511 | 0 | 0 | 0 | 0 | 0 | 44.539 | 0 | 44.20 | 43.11 | 80.17 | 79.08 | 55.6 | 41.6 | - | 56.2 |
| B4C Drum Controlled Reactor | 5.0 | 7 | 6 | 143.92945 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 32.39 | 31.59 | 58.75 | 57.95 | 174.6 | 160.6 | 141.43 | 64.2 |
| | 5.1 | 7 | 5.5 | 142.73779 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 32.39 | 31.59 | 58.75 | 57.95 | 98.0 | 84.0 | - | - |
| Worth of Polyethylene Added to Core Proper | 6.0 | 6 | 7 | 174.24874 | 0 | 0 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 104.2 | 90.2 | 172.49 | 51.2 |
| | 6.1 | 6 | 6.5 | 172.63355 | 0 | 0 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 21.5 | 7.5 | - | 51.2 |
| | 6.2 | 6 | 7 | 174.24874 | 0 | 0.372 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 184.8 | 170.8 | - | - |
| | 6.3 | 6 | 5 | 167.92643 | 0 | 2.229 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 193.8 | 179.8 | 164.43 | 51.4 |
| | 6.4 | 6 | 4.5 | 166.35631 | 0 | 2.229 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 113.1 | 99.1 | - | - |
| | 6.5 | 6 | 5 | 167.83595** | 0 | 2.229 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 183.0 | 169.0 | - | 51.4 |
| | 6.6 | 6 | 5 | 167.83595 | 0 | 1.486 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 50.1 | 36.1 | - | - |
| | 6.7 | 6 | 5 | 167.83595 | 0 | 0.743 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | -94.7 | -108.7 | - | - |
| | 6.8 | 6 | 5 | 167.83595 | 0 | 0 | 9.54 | 0 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | -228.2 | -242.2 | - | - |
| | 6.9 | 6 | 5 | 167.83595 | 0 | 0 | 9.54 | 6.1424 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | -229.8 | -243.8 | - | - |
| | 6.10 | 6 | 5 | 167.83595 | 0 | 0.743 | 9.54 | 6.1424 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | -84.9 | -98.9 | - | - |
| | 6.11 | 6 | 5 | 167.83595 | 0 | 1.486 | 9.54 | 6.1424 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 49.6 | 35.6 | - | - |
| | 6.12 | 6 | 5 | 167.92643 | 0 | 1.486 | 9.54 | 6.1424 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 58.2 | 44.2 | - | - |
| | 6.13 | 6 | 5 | 167.92643 | 0 | 2.229 | 9.54 | 6.1424 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 189.6†† | 175.6†† | 164.78 | 50.9 |
| | 6.14 | 6 | 4.5 | 166.31666 | 0 | 2.229 | 9.54 | 6.1424 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | 107.6†† | 93.6†† | - | 50.9 |
| | 6.14 | 6 | 4.5 | 166.22618 | 0 | 1.486 | 9.54 | 6.1424 | 21.70 | 0 | 4.12 | 44.20 | 43.11 | 80.17 | 79.08 | -32.4†† | -46.4†† | - | - |

*All drums full in.

†Corrected by -14¢ for polyethylene around the neutron detectors.

§Cores 1.0, 1.1, and 1.2 are three-zone, power-flattened cores. The loading pattern of 6 rods, 1 wire in Zone 1; 7 rods, no wires in Zone 2; and 7 rods, 4 wires in Zone 3 remained the same for all three cores (see Figure 26).

**Adjustments have been made in the loading of the central fuel element to accommodate a Cf$^{252}$ source.

††A constant reactivity value of 29.4¢ has been added (see text, p. 111).

In Column 3 of Table 2 are listed the loading patterns for the various cores, the term "rods" referring to the number of uranium rods [each 0.432 cm (0.170 in.) in diameter by 37.508 cm (14.767 in.) long] in each fuel element and the term "wires" referring to the number of uranium wires [each 0.152 cm (0.060 in.) in diameter by 37.465 cm (14.75 in.) long] in each fuel element. Except for Cores 1.0 through 1.2 inclusive, and certain cores, such as 4.3, 5.1, etc., which were used to measure the core-averaged worth of uranium, most critical systems contained a uniform loading of uranium fuel such that the mass of uranium in each fuel element did not differ from the average by more than ±1.2 gm. As noted above, the first series of experiments dealt with a 3-zoned, power-flattened core and, in this case, the listed loading pattern refers to the number of uranium rods and wires in each fuel element in each zone. Specifically, Zone 1 (see Section II-B) contained 6 rods and 1 wire, Zone 2 contained 7 rods and no wires, and Zone 3 contained 7 rods and 4 wires. This loading pattern applied to all three cores (1.0, 1.1, and 1.2).

Normally the core-averaged worth of fuel was determined, where required, by a uniform removal of fuel from the core; i.e., by removing one wire from every fuel element. In some cases, however, the removal of this much fuel (approximately 3 kg) would have rendered the reactor subcritical. Consequently, the procedure was altered such that one wire was removed from every other fuel element, thus preserving some reasonable uniformity. Where in Column 3 of Table 2 a fractional wire count is indicated (Cores 4.3, 5.1, etc.), the latter procedure was followed.

Column 4 of Table 2 shows the total mass of uranium fuel in the reactor, the mass being distributed, except for Cores 1.0, 1.1, and 1.2, in a uniform manner among all fuel elements. Normally the total number of fuel elements is 247 except in the case of the $B_4C$-controlled system in which the 11 fuel elements in each of the six drums were removed, thus producing a 181-element system.

As was pointed out above, Columns 5 through 12 of Table 2 indicate the types and masses of additional materials that were present in the various cores in addition to the fuel and the materials delineated in Table 1. All entries in these columns, except those in Columns 5 and 12, pertain to uniform material distribution within or between fuel elements. In Core 1.0, for example, no

polyethylene was present around the core, but 21.70 kg of Ta foil, 15.15 kg of W fuel, and 4.12 kg of Hf were distributed uniformly among the 247 fuel elements in all three zones. Core 1.1 incorporated, in addition to the Ta, W, and Hf, a full polyethylene shield 15.24 cm (6 in.) in thickness and 352.667 kg in weight around the reactor. Core 1.2 was identical to Core 1.1 except that all of the top and part of the bottom portions of the polyethylene shield were removed.

Columns 15 and 16 of Table 2 indicate the total mass of cylindrical axial Mo reflector segments on the top and bottom of the core. Normally each solid Mo reflector segment is 1.493 cm (0.588 in.) in diameter by 10.00 cm (3.94 in.) long and weighs, on the average, 178.95 gm. One segment is placed at the top and one at the bottom of each fuel element. Thus, in a core containing 247 fuel elements, all of the Mo segments making up the upper reflector (disregarding the eccentric segments) will weigh 44.20 kg and all of the Mo segments making up the lower reflector will also weigh 44.20 kg. In the series of experiments (Cores 3.0 through 3.3) dealing with the reactivity worths of axial reflectors, 247 of the cylindrical reflector components (which represent 55.1% of axial reflector mass) were cut in such a way as to produce 247 one-half and 494 one-quarter length segments. Thus the upper and lower axial reflectors could be reduced in mass to roughly 72.4 and 58.6% by weight of their previous values.

Column 17 of Table 2 lists the as-measured system excess reactivities for the various cores. These reactivity values refer to the excess or degree of subcriticality that would exist if all drums were driven to their most reactive position. For the normal, fueled control drum reactor, this position corresponds to fuel full-in. For the $B_4C$-controlled reactor, this position corresponded to the $B_4C$ sector full-out; i.e., turned so that the $B_4C$-filled canister on the drum is as far from the core axis as possible.

Figure 8 showed two large polyethylene boxes into which the neutron detectors for Channels 3, 4, 5, and 6 were placed. The polyethylene was utilized in order to increase the sensitivity of the chambers and therefore improve the accuracy of various experimental measurements. The boxes do, however, introduce a systematic error in that they act as reflectors and consequently increase the system reactivity relative to a completely isolated system. The reactivity error inherent in the boxes has been measured on several occasions

by the process of noting the changes in the critical position of a drum with and without the boxes present. This information, in addition to that from a drum calibration curve, indicated that both polyethylene boxes (that around Channels 3 and 4 and that around Channels 5 and 6) add 14.0¢ to the reactivity of the reactor. Thus Column 18 of Table 2 shows the excess reactivity or degree of subcriticality that would exist if these boxes were not present. Other perturbations of this type — such as the sample changer table shown in Figure 1 and the polyethylene boxes around the detectors for Channels 1 and 2 — have been investigated, but have been shown to represent statistically insignificant effects. For Cores 1.1 and 1.2, where the polyethylene shield is present around the core, no polyethylene boxes were required; consequently no correction of the above type is needed. Finally, in Columns 16 and 17 of Table 2 are listed the critical mass values and conversion factors, respectively, for the various cores. The conversion factors are the values for the core-averaged worth of 1 kg of fuel material as determined by the uniform removal of some quantity of fuel. By multiplying the corrected excess reactivity value (Column 18) by the conversion factor, a value for the mass of fuel corresponding to this excess is obtained. This excess mass is then subtracted from the total fuel loading to obtain the critical mass. Since critical mass values were not required for some cores and since some cores constructed during the current program were nearly identical to some of the cores studied on the previous program, the core averaged worth of fuel was not always measured. The conversion factor of 50.6¢/kg, for example, was determined during the previous program (see Reference 1, page 133) and was considered applicable to several cores listed in the table. All other values were measured specifically for the core to which they apply.

## 3. Reactivity Worths of Non-Fuel Materials

By inspection of Table 2, the reactivity changes associated with various material alterations can be derived. A summary of some of these values is given in Table 3. For the first series of experiments, the initial, corrected, all-drums-in excess reactivity for the base case (the 3-zoned, power-flattened core without a polyethylene shield) was 30.6¢. The addition of the full polyethylene shield increased the reactivity to 136.7¢, thus indicating a total worth of +106.1¢ for the shield. After removing all of the upper axial shield and a portion of the lower shield in accordance with the details set forth in Section II-B

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TABLE 3

SUMMARY OF REACTIVITY WORTHS

| Item | Base Case Core Numbers | Reference Core Numbers | Reactivity Worth* (¢) |
|---|---|---|---|
| Full Polyethylene Shield | 1.0 | 1.1 | +106.1 |
| Radial Polyethylene Shield Alone[†] | 1.0 | 1.2 | +90.5 |
| 9.54 kg of Ta Wire | 2.0 | 2.1 | -19.0[§] |
| One-Half-Height Axial Reflector[**] | 2.0 | 3.1 | -156.8 |
| One-Quarter-Height Axial Reflector[**] | 2.0 | 3.1, 3.2, 3.3 | -288.2 |
| 29.41 kg of W Rod | 4.0 | 4.1 | +71.6 |
| 44.54 kg of W Rod and Foil | 4.0 | 4.2 | +122.4 |
| 2.229 kg of Polyethylene Strips (80.25 kg of Ta in Core) | 6.5 | 6.8 | +411.2 |
| 2.229 kg of Polyethylene Strips (86.39 kg of Ta in Core) | 6.9 | 6.13[*] | +409.7 |

*Total excess reactivity corrected by 9.7¢ for difference in U mass loading between Cores 6.9 and 6.13. The 9.7¢ value is based upon the average value from Cores 6.3 and 6.5 and from Cores 6.11 and 6.12.

†All of the upper, but only a portion of the lower axial shield could be removed for this measurement (see Section II-B-1).

§A more direct measurement by means of inverse kinetics techniques yielded a more accurate value of 17.6¢ for this quantity.

**Only that portion of the axial reflector comprised of solid cylinders of Mo was changed. "One-half-height" means that approximately one-half of the height of the Mo was removed. "One-quarter-height" means that approximately three-quarters of the height of the Mo was removed.

of this report, a decrease in the all-drums-in excess of 121.1¢ was observed. It follows, therefore, that the radial shield alone is worth approximately 90.5¢.

Upon reconfiguring the core in order to achieve a uniformly loaded 247 fuel element configuration for the base case for Ta wire addition, a system excess reactivity of 168.5¢ was measured. This core (2.0) contained no polyethylene, W, Hf, or Ta foil or wire, the total Ta content, in other forms, being 49.64 kg. The addition of 1 Ta wire [0.27 cm (0.110 in.) in diameter, 37.39 cm (14.7 in.) long, and weighing an average of 38.61 gm] to each of 247 fuel elements reduced the excess to 149.5¢. Consequently the 9.54 kg of Ta was worth -19.0¢. A more

accurate value, which was based upon measuring the reactivity at a fixed drum position when the Ta wire was both absent and present, yielded a value of -17.3¢.

Using Core 2.0 also as the base case for the series of experiments dealing with the reactivity effects of reducing the heights of portions of the upper and lower Mo reflectors, one notes that the excess reactivity decreased from 168.0¢ (Core 2.0) to 11.7¢ (Core 4.1) as a result of shortening the cylindrical Mo segments from 10.00 cm (3.94 in.) to 4.90 cm (1.93 in.) in length. This procedure reduced the reflector mass to about 72.4% of the nominal value and resulted in a change of 156.8¢. In a like manner, the reactivity change resulting from the reduction of the cylindrical axial reflector segments by a factor of about 4 [i.e., from 10.00 cm (3.44 in.) to 2.45 cm (0.96 in.)] can be derived from the data of Table 2. In this case, however, an intermediate step (Core 4.2), involving a fuel change, had to be made. The excess reactivity changed from 151.2¢ (Core 4.2) down to 19.8¢ (Core 4.3) in response to a reduction of segment length from 4.90 cm (1.93 in.) to 2.45 cm (0.96 in.). This reactivity change (131.4¢), when combined with that corresponding to a reduction in segment height from 10 cm (3.94 in.) to 4.90 cm (1.93 in.), implies a total reactivity reduction of 288.2¢ for a reflector mass reduction to 58.6% of the nominal value.

The base case for establishing the reactivity worth of tungsten was Core 4.0 which, like Core 2.0, contained no polyethylene W, Hf, or Ta wire and foil initially. The excess reactivity increased from 9.5 to 81.1 to 131.9¢ as the total W content of the cores increased from 0 to 29.41 to 44.54 kg, respectively. These results indicate that 29.41 and 44.54 kg of W have reactivity worths of +71.6 and +122.4¢, respectively.

The reactivity effects of adding 2.229 kg of polyethylene strips to a uniformly loaded core containing, in one case, 80.25 kg of Ta (Core 6.8) and, in another case, 86.39 kg of Ta (Core 6.9), can be derived to be +411.2 and +409.7¢, respectively, as indicated in Table 3. The value of 411.2¢ corresponds to the change in the system reactivity values for Cores 6.8 and 6.5. The value of 409.7¢ is based upon the value of -243.8¢ for the degree of subcriticality of Core 6.9 and the excess reactivity value of 175.6¢ for Core 6.13. The latter excess reactivity value must, however, be decreased by 9.7¢ since Core 6.13 contains 90.48 additional grams of fuel. The latter correction is obtained directly from an average of the changes observed in going from Core 6.3 to Core 6.5 and from Core 6.11 to Core 6.12.

## 4. Reactivity Worth of Fuel

In a manner similar to that outlined in Section II-A-3, the reactivity worth of fuel for various core conditions can be derived on the basis of the data of Table 2. A summary of these results is contained in Table 4. The column labeled "Core Number" indicates the initial and final core designations where the initial and final cores differ only by the amount of fuel present and this difference is delineated in the column labeled "Change in Fuel Loading." The column headed "Principal Core Constituents (Non-Fuel)" refers to the major materials located in the active core when all drums are turned to their most reactive position. In contrast to the other materials, the amount of Ta metal may vary from one case to the next. As can be seen by reference to Tables 1 and 2, the 3rd and 4th series of cores contain the same quantities of Ta (49.01 kg), whereas the 5th contains 35.91 kg. Cores 6.3 and 6.4 each contain 80.25 kg, and Cores 6.13 and 6.14 each contain 86.39 kg. These variations should be taken into account when intercomparing the core-averaged worth of fuel.

## 5. Drum Calibrations

Individual drum calibrations were routinely conducted in most of the cores listed in Table 2, although these calibrations did not always involve a measurement of the worth over the complete 180° span of rotation. Representative samplings of these drum calibrations are shown in Figures 9 through 17, and are correlated with the various cores in accordance with the data shown in Table 5, where, in addition, the total control swing is listed if available.

The drum calibration curve for Core 1.0 (Figure 9) was actually obtained on the previous program (see Figure 31 of Reference 1), but is repeated here for purposes of completeness. Figure 11 is a drum calibration curve applying not only to Core 2.0, but also to Cores 3.0 and 4.0. Actual measurements of drum worths were made for the latter two cores, but yielded virtually identical results to the one shown here.

Figure 15 shows the results for a control drum in Core 4.2, which contains 44.54 kg of W foil. A calibration for a drum in the core which contained 29.41 kg of W was also performed, but only out to about 80 degrees of arc. Over this span, the reactivity values were in good agreement with the data presented here.

## TABLE 4

## REACTIVITY WORTH OF FUEL IN VARIOUS CORES

| Core Number | | Principal Core Constituent (Non-Fuel) | Cylindrical Mo Reflector Component Length | Control System | Change in Fuel Loading (kg) | Reactivity Change (¢) | Worth Per Unit Mass (¢/kg) |
|---|---|---|---|---|---|---|---|
| Initial | Final | | | | | | |
| 3.0 | 4.0 | Ta, $Li_3^7N$ | Full | Fuel | 3.0215 | 150.6 | 49.8 |
| 3.1 | 3.2 | Ta, $Li_3^7N$ | 1/2 | Fuel | 2.3246 | 139.5 | 60.0 |
| 4.2 | 4.3 | Ta, $Li_3^7N$, W | Full | Fuel | 1.6067 | 90.3 | 56.2 |
| 5.0 | 5.1 | Ta, $Li_3^7N$, Mo | Full | $B_4C$ | 1.1917 | 76.6 | 64.2 |
| 6.0 | 6.1 | Ta, $Li_3^7N$, Hf | Full | Fuel | 1.61519 | 82.7 | 51.2 |
| 6.3 | 6.4 | Ta, $Li_3^7N$, Hf, Polyethylene | Full | Fuel | 1.57012 | 80.7 | 51.4 |
| 6.13 | 6.14 | Ta, $Li_3^7N$, Hf, Polyethylene | Full | Fuel | 1.60977 | 82.0 | 50.9 |
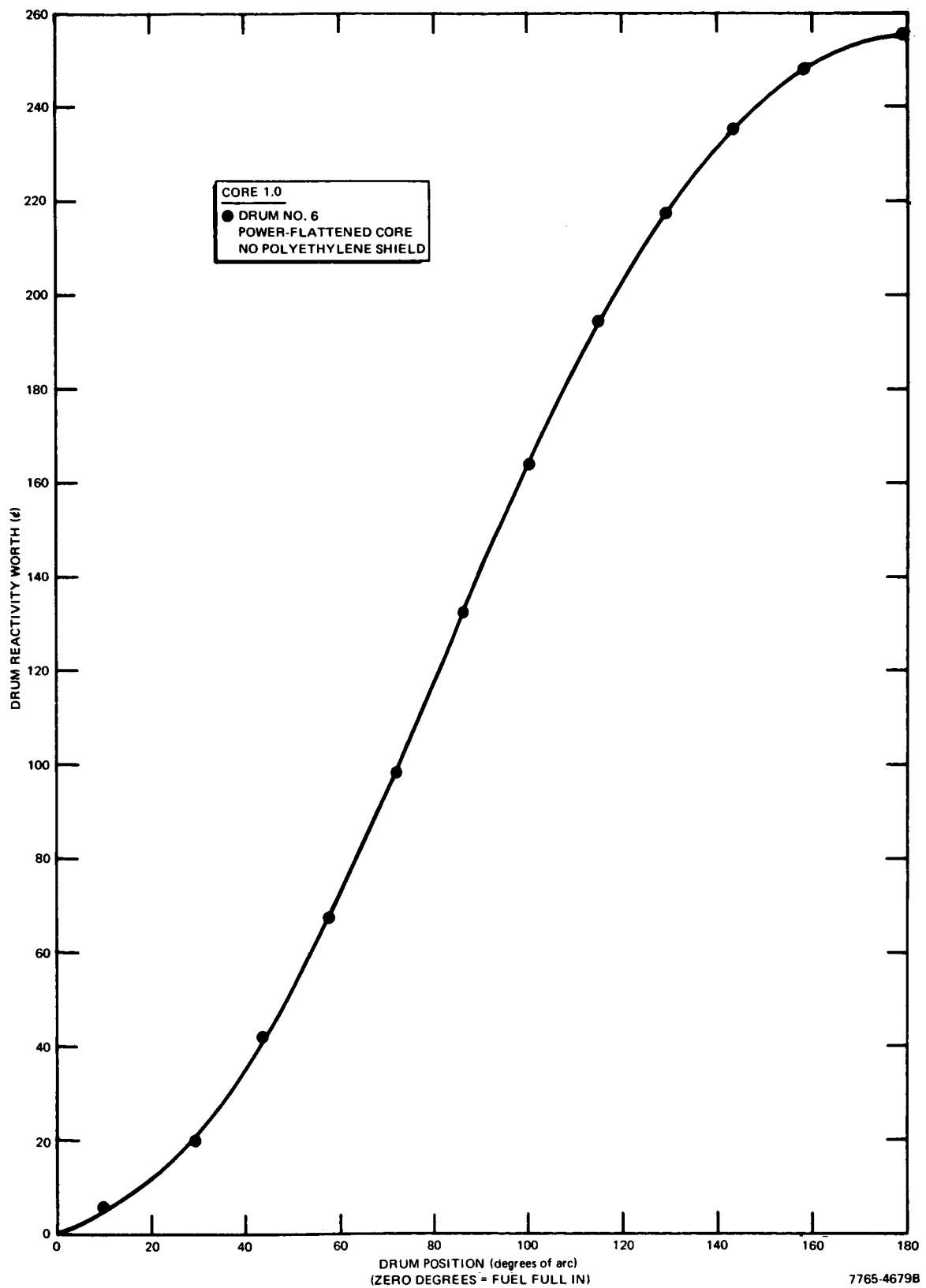
Figure 9.   Drum Worth Curve for Core 1.0
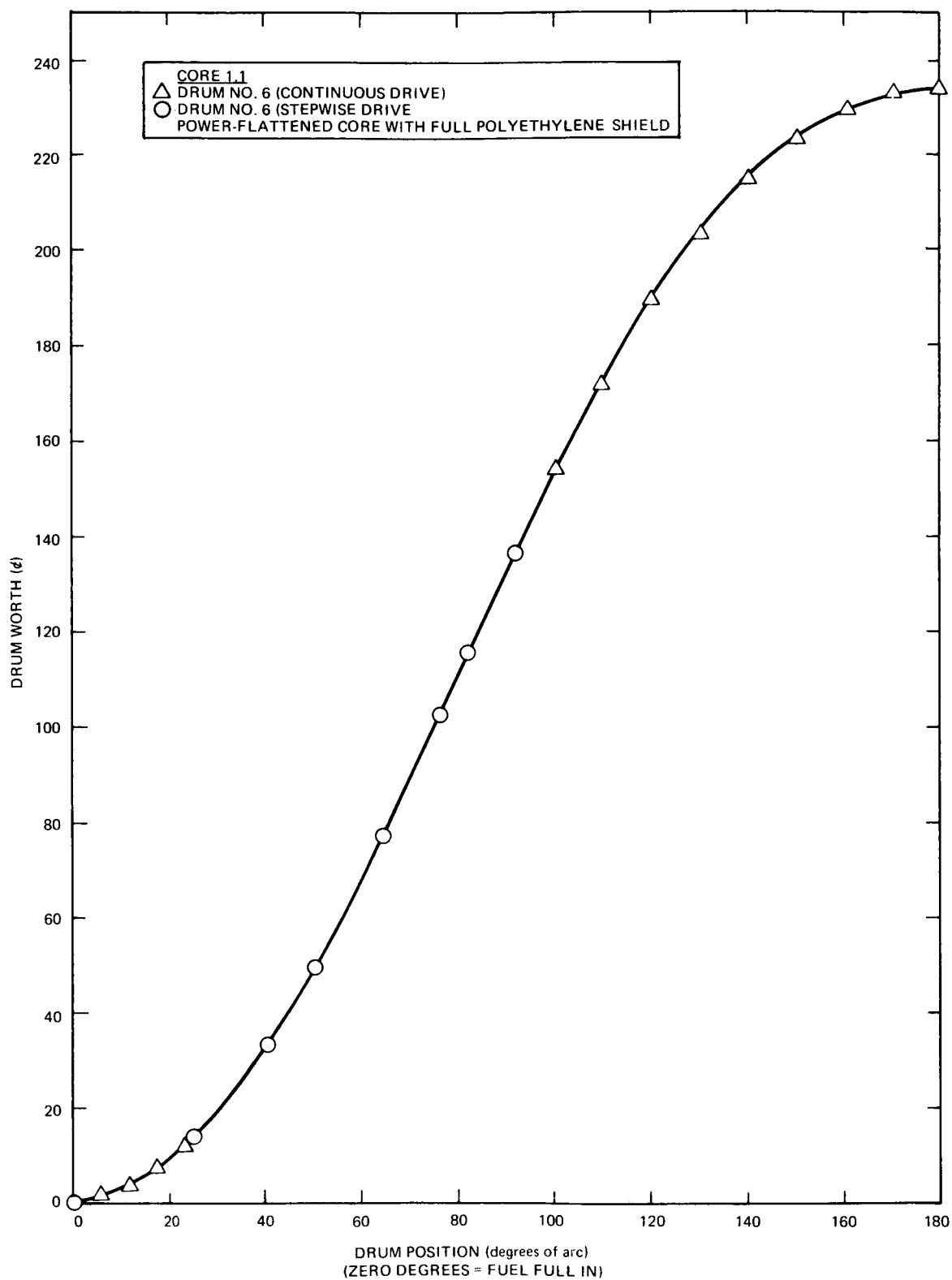
41

Figure 10. Drum Worth Curve for Core 1.1
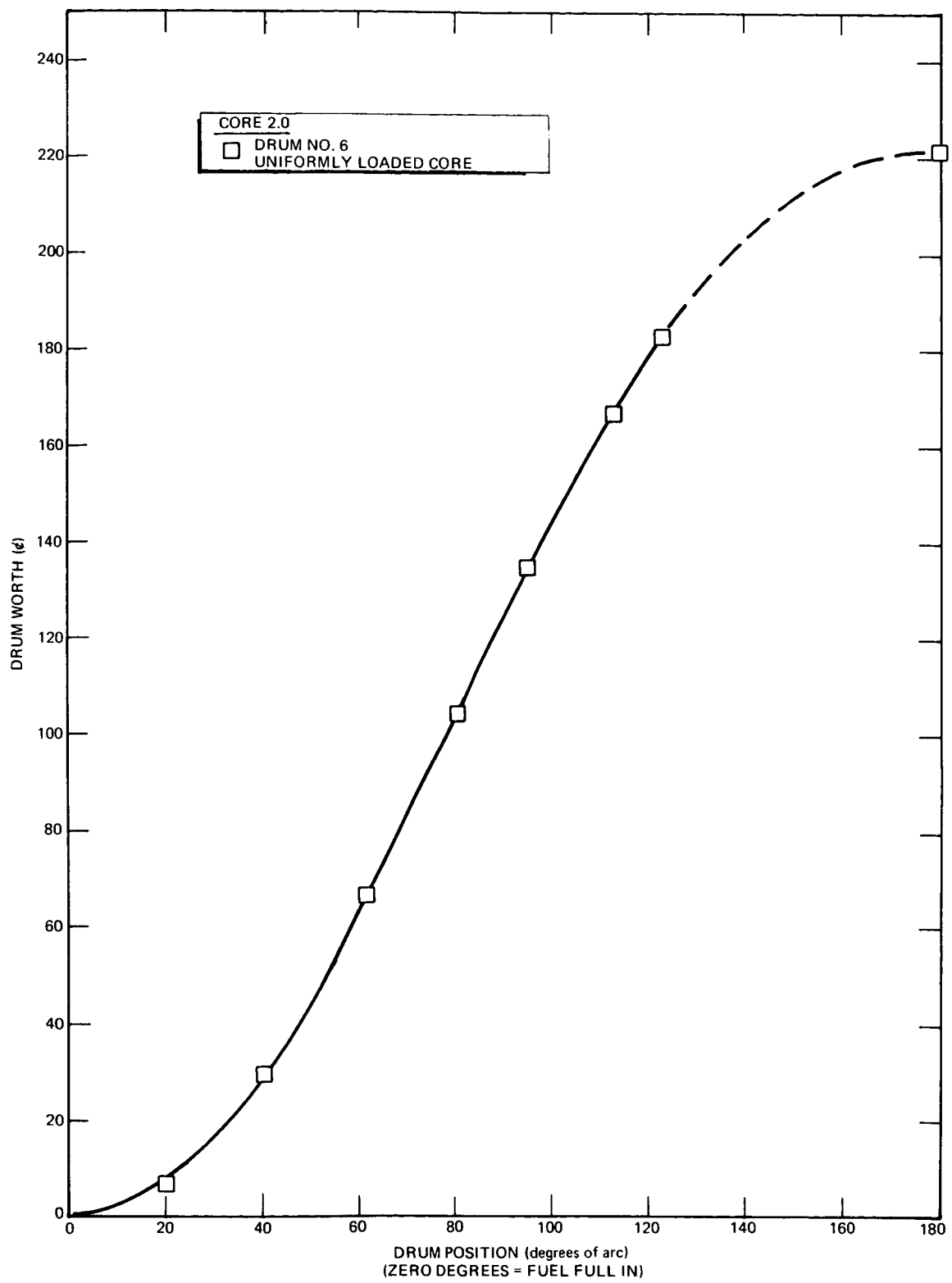
6526-4601

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Figure 11.   Drum Worth Curve for Core 2.0

6526-4602

CORE 2.1

○ DRUM NO. 6
△ DRUM NO. 3

UNIFORMLY LOADED CORE
9.54 kg OF TANTALUM WIRE IN PLACE

DRUM WORTH (¢)

DRUM POSITION (degrees of arc)
(ZERO DEGREES = FUEL FULL IN)
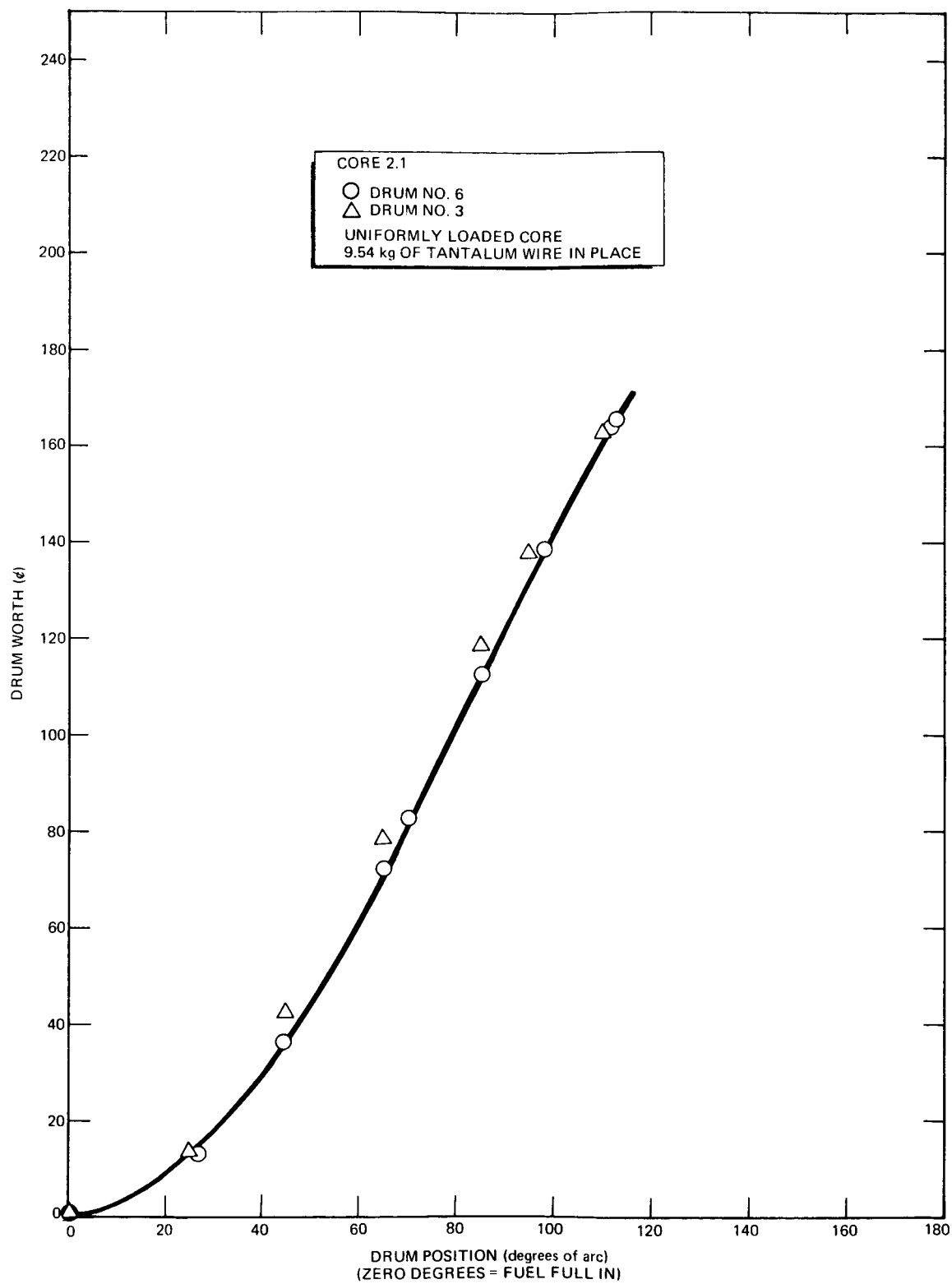
6526-4603

Figure 12.   Drum Worth Curve for Core 2.1

44

CORE 3.2
□ DRUM NO. 6 (CONTINUOUS DRIVE)
△ DRUM NO. 6 (STEPWISE DRIVE)
UNIFORMLY LOADED CORE
ONE-HALF LENGTH MOLYBDENUM REFLECTORS (4.90 cm)

DRUM WORTH (¢)

DRUM POSITION (degrees of arc)
(ZERO DEGREES = FUEL FULL IN)
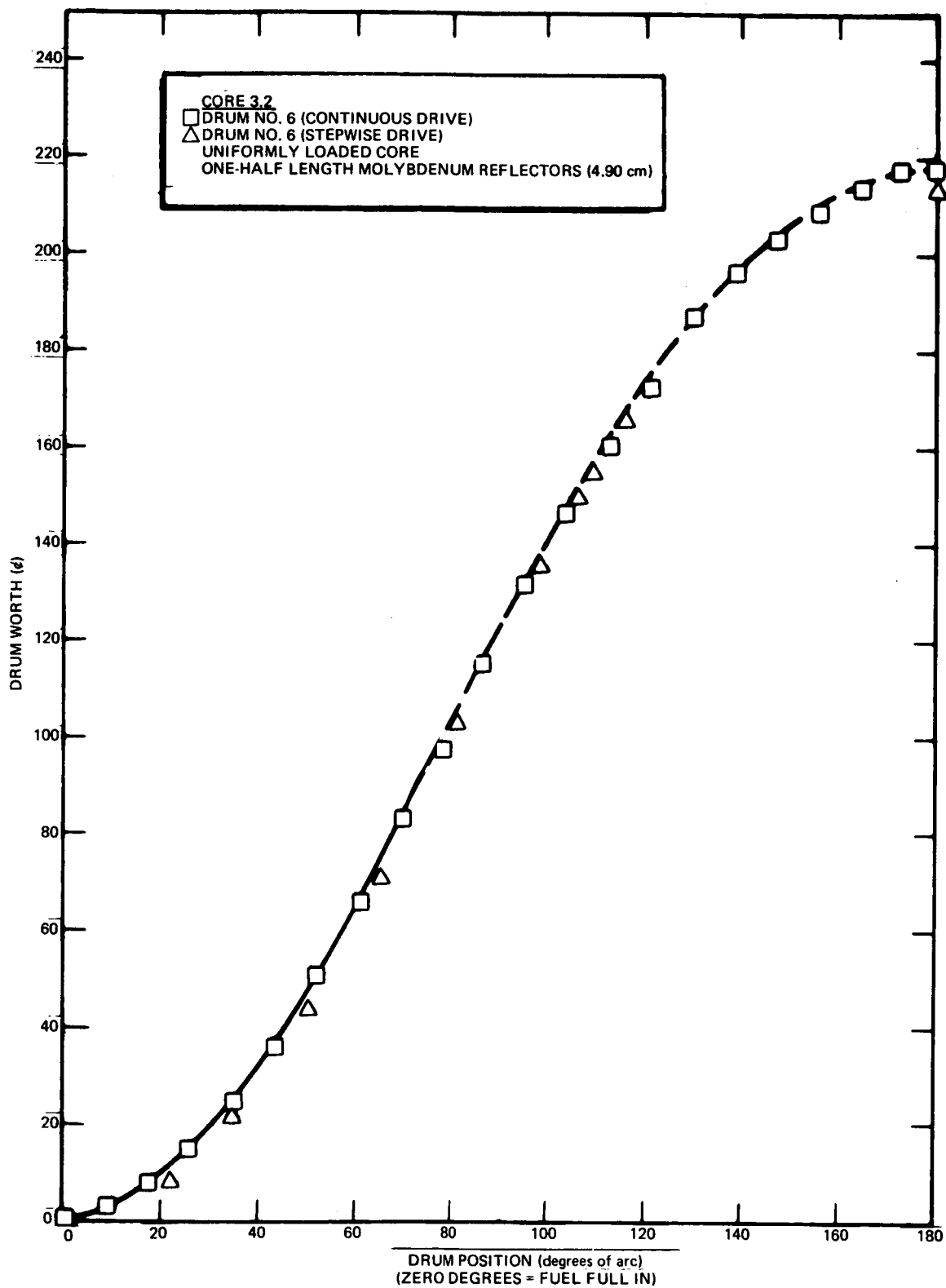
6526-4604

Figure 13.   Drum Worth Curve for Core 3.2
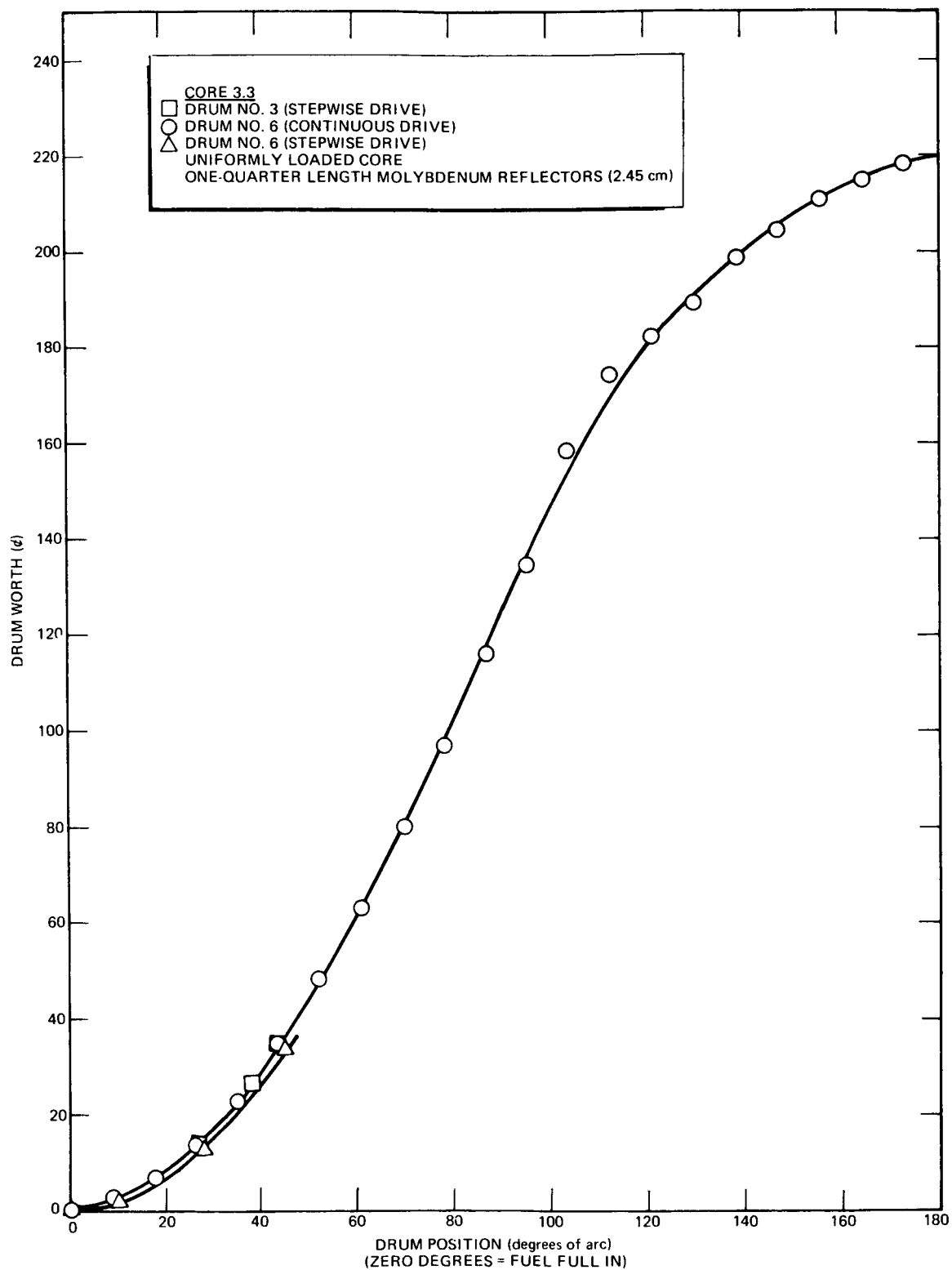
45

Figure 14. Drum Worth Curve for Core 3.3
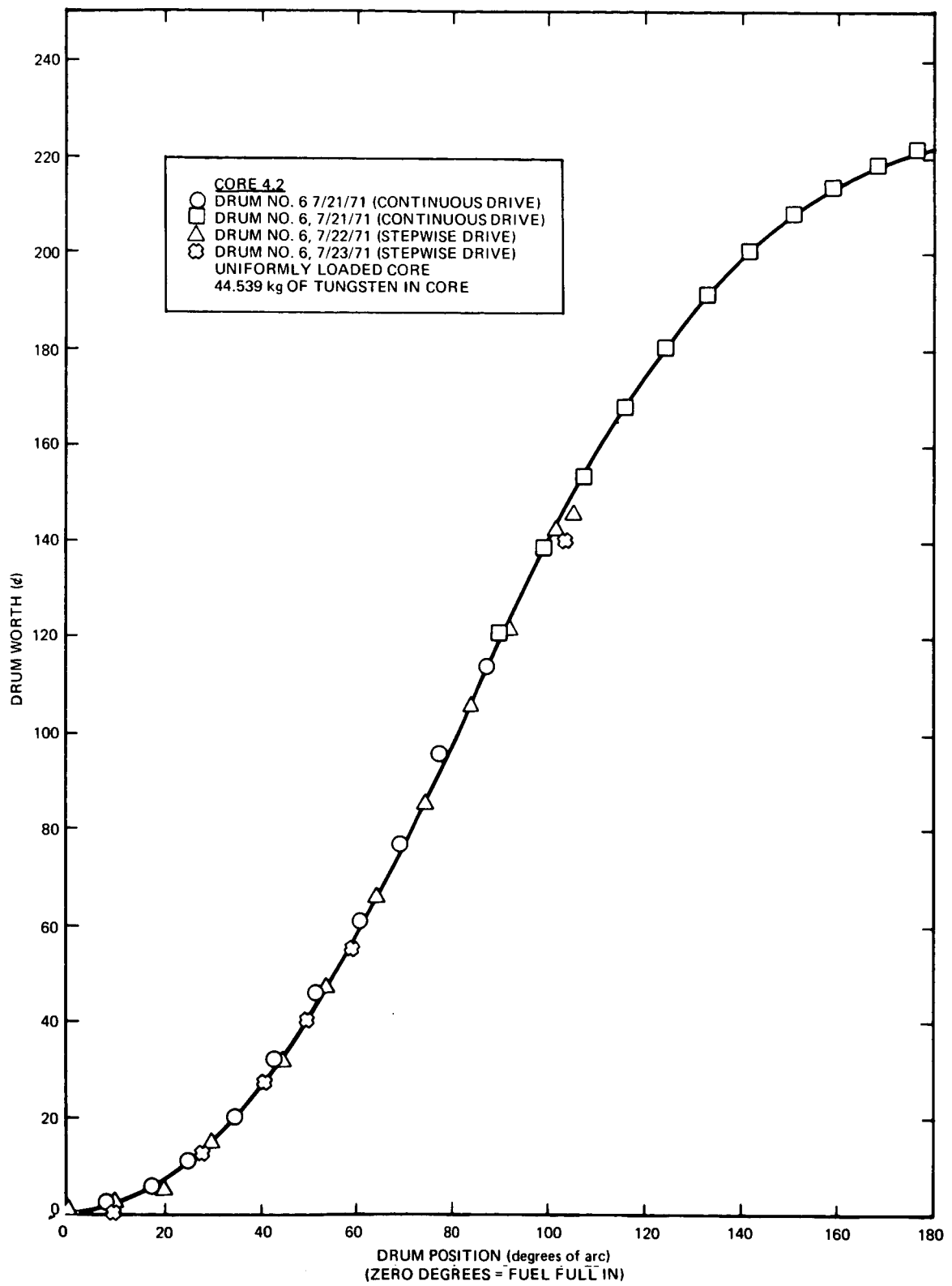
6526-4605

Figure 15. Drum Worth Curve for Core 4.2

6526-4606

CORE 5.0

DRUM NO. 6
UNIFORMLY LOADED
BORON CARBIDE CONTROLLED REACTOR

DRUM WORTH (¢)

DRUM POSITION (degrees of arc)
(ZERO DEGREES = MOLYBDENUM PLATE FULL IN)
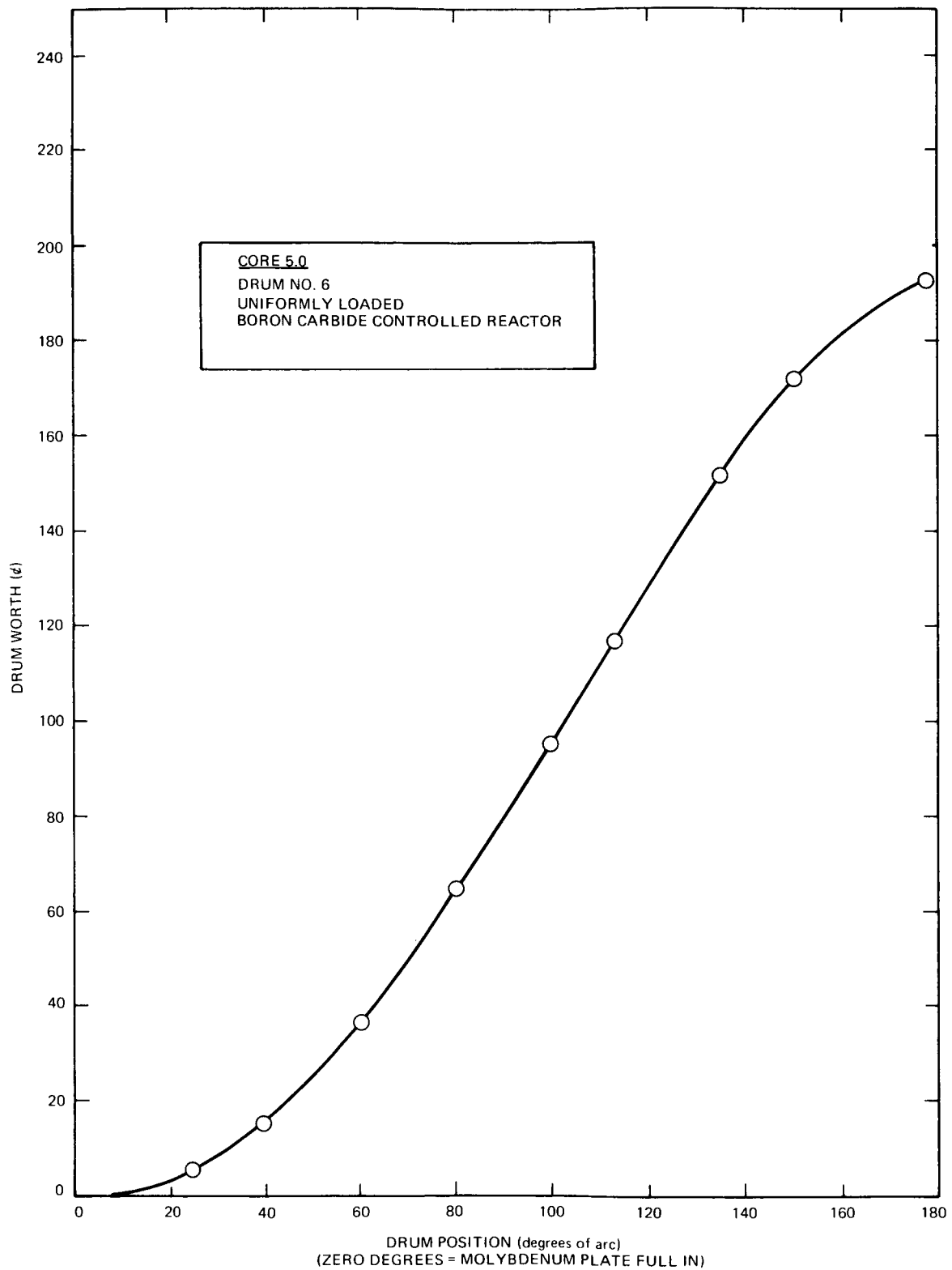
6526-4607

Figure 16.  Drum Worth Curve for Core 5.0

CORE NO. 6.3

DRUM NO. 3
UNIFORMLY LOADED CORE
2.229 kg OF POLYETHYLENE IN CORE (360 STRIPS)

DRUM WORTH (¢)

DRUM POSITION (degrees of arc)
(ZERO DEGREES = FUEL FULL IN)
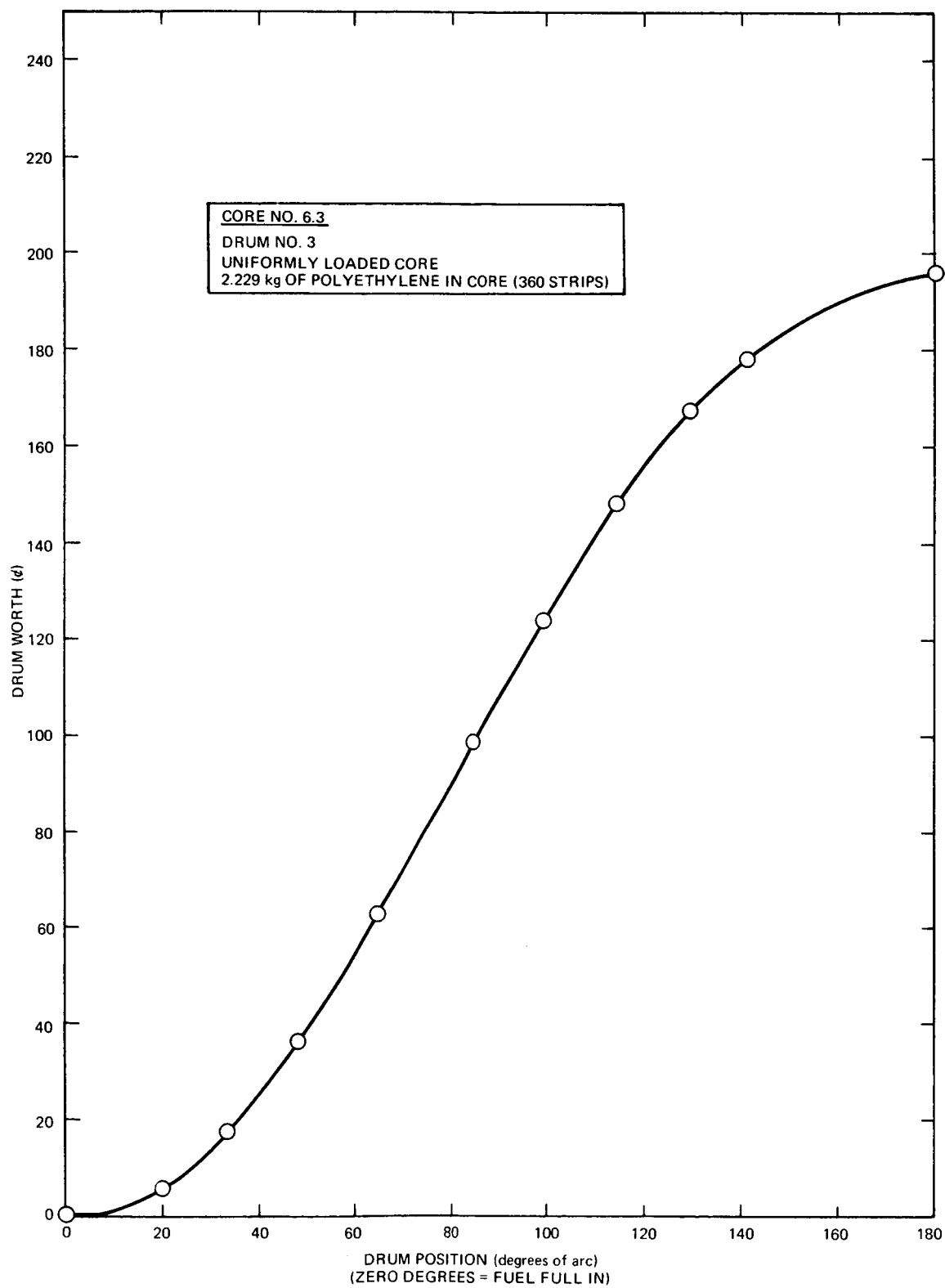
6526-4608

Figure 17.   Drum Worth Curve for Core 6.3
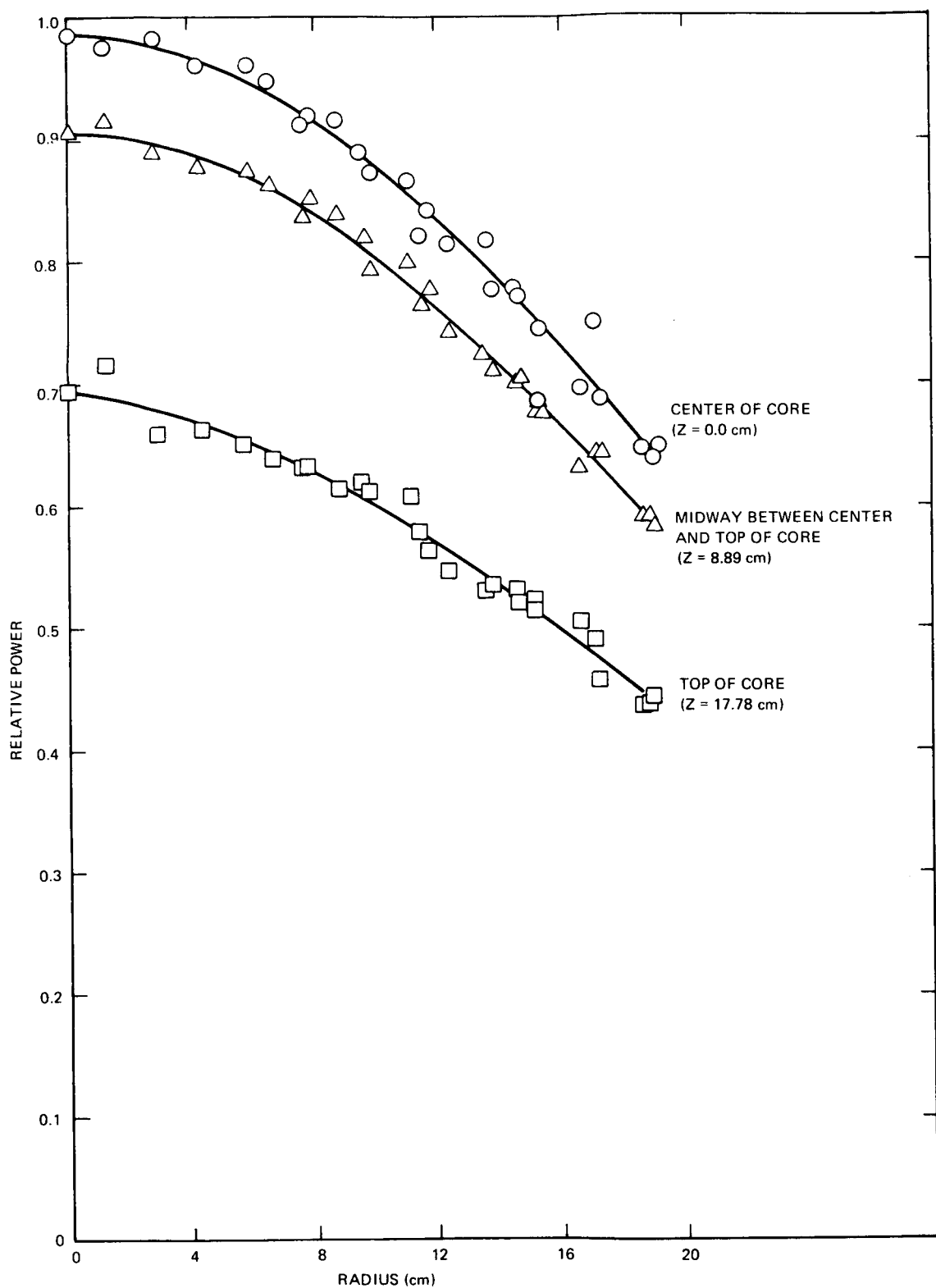
49

Figure 18.  Radial Power Distribution (Polyethylene Shielded Core)

6526-4609

TABLE 5

CORRELATION OF DRUM CALIBRATIONS AND CORES

| Core Number | Figure Number | Core Description | Control Swing* ($) |
|---|---|---|---|
| 1.0 | 9 | Power Flattened Core — No Polyethylene Shield | 2.57 |
| 1.1 | 10 | Power Flattened Core — Full Polyethylene Shield | 2.34 |
| 2.0 | 11 | Uniformly Loaded Core (See Composition 2, Reference 1) | 2.21 |
| 2.1 | 12 | Uniformly Loaded Core with 9.54 kg Ta Added | - |
| 3.1 | 13 | Uniformly Loaded Core — 4.90-cm Reflector | 2.13 |
| 3.3 | 14 | Uniformly Loaded Core — 2.45-cm Reflector | 2.20 |
| 4.2 | 15 | Uniformly Loaded Core — 44.54 kg W | 2.22 |
| 5.0 | 16 | Uniformly Loaded Core — $B_4C$ Drum | 1.93 |
| 6.3 | 17 | Uniformly Loaded Core — 360 Polyethylene Strips | 1.96 |

*Ta or $B_4C$ from Full-In to Full-Out

6. Power Distributions

Four sets of power distribution measurements, each consisting of axial and radial components, were conducted during this program and are presented graphically in Figures 18 through 25, and are tabulated in Section II of this report. In the case of the polyethylene shielded core (1.1), more emphasis was placed on the radial component than the axial, with distributions being obtained at the core midplane, at the top of the core and in a plane half way between these two planes. Axial distributions were measured within fuel element positions 0-1, 5-3, 11-11, and 10-2. In Cores 4.2 and 4.3, fewer radial points were
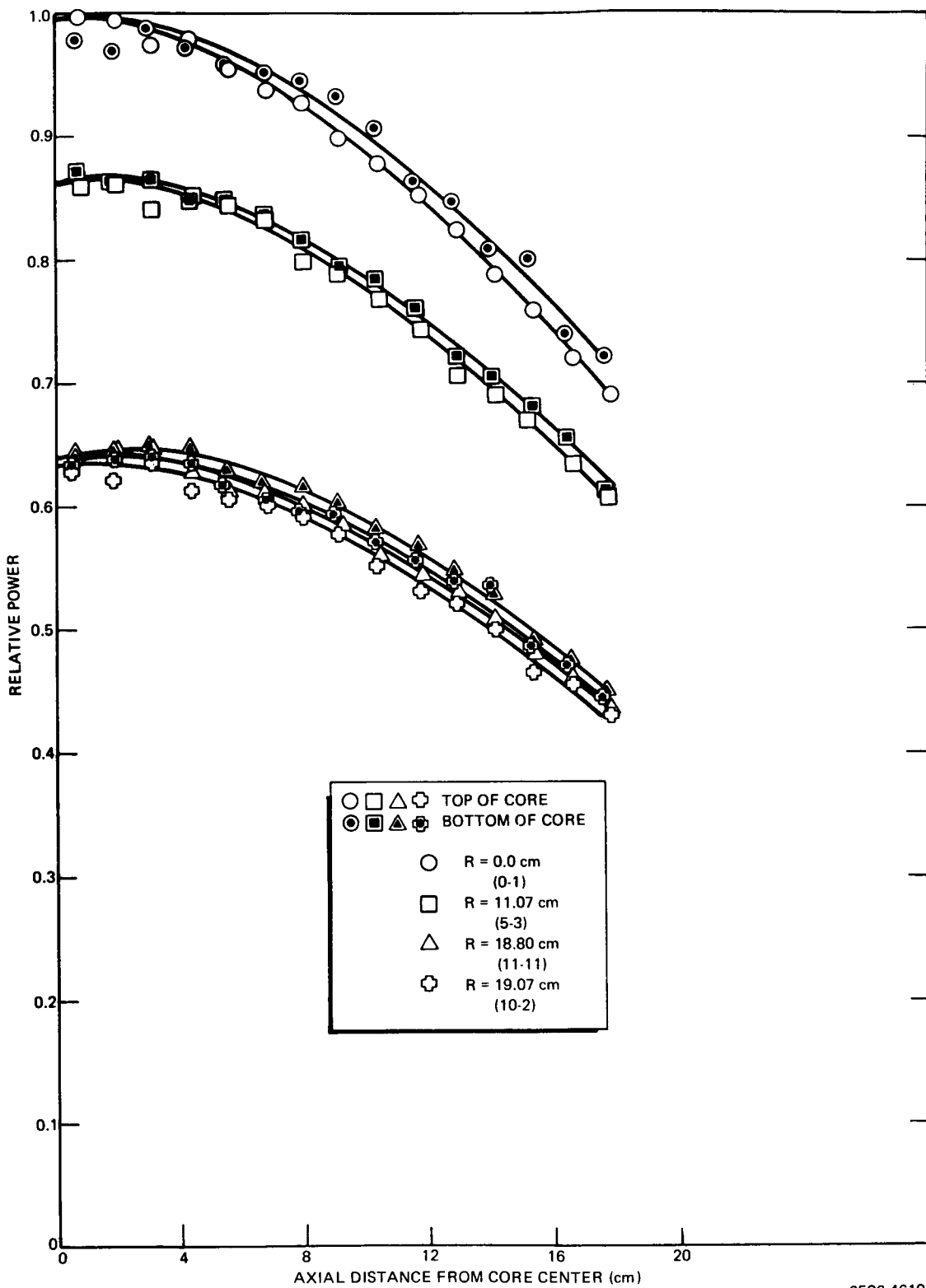
Figure 19. Axial Power Distribution (Polyethylene Shielded Core)
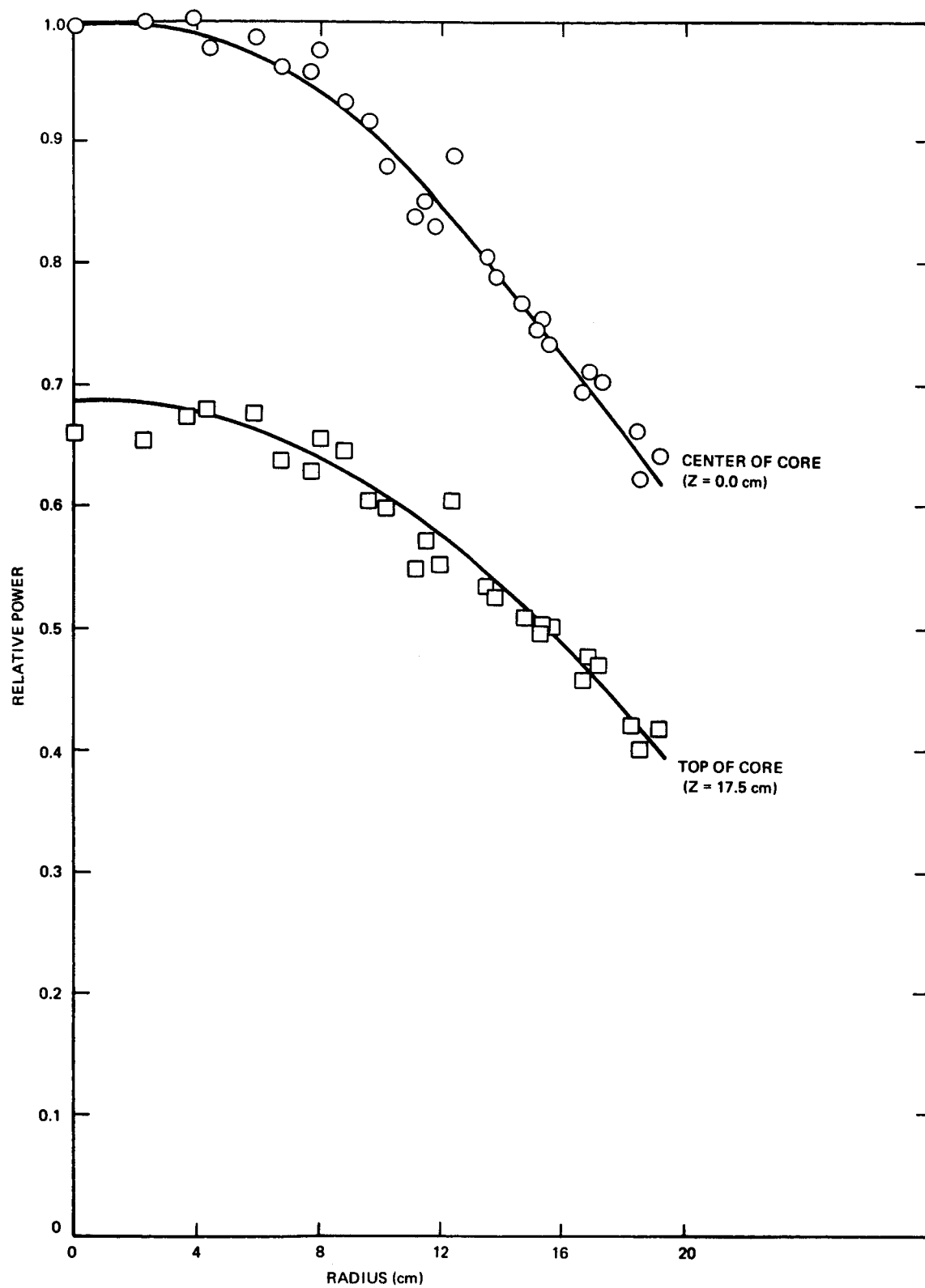
Figure 20. Radial Power Distribution (4.90-cm-long Mo Reflector)

6526-4611

53
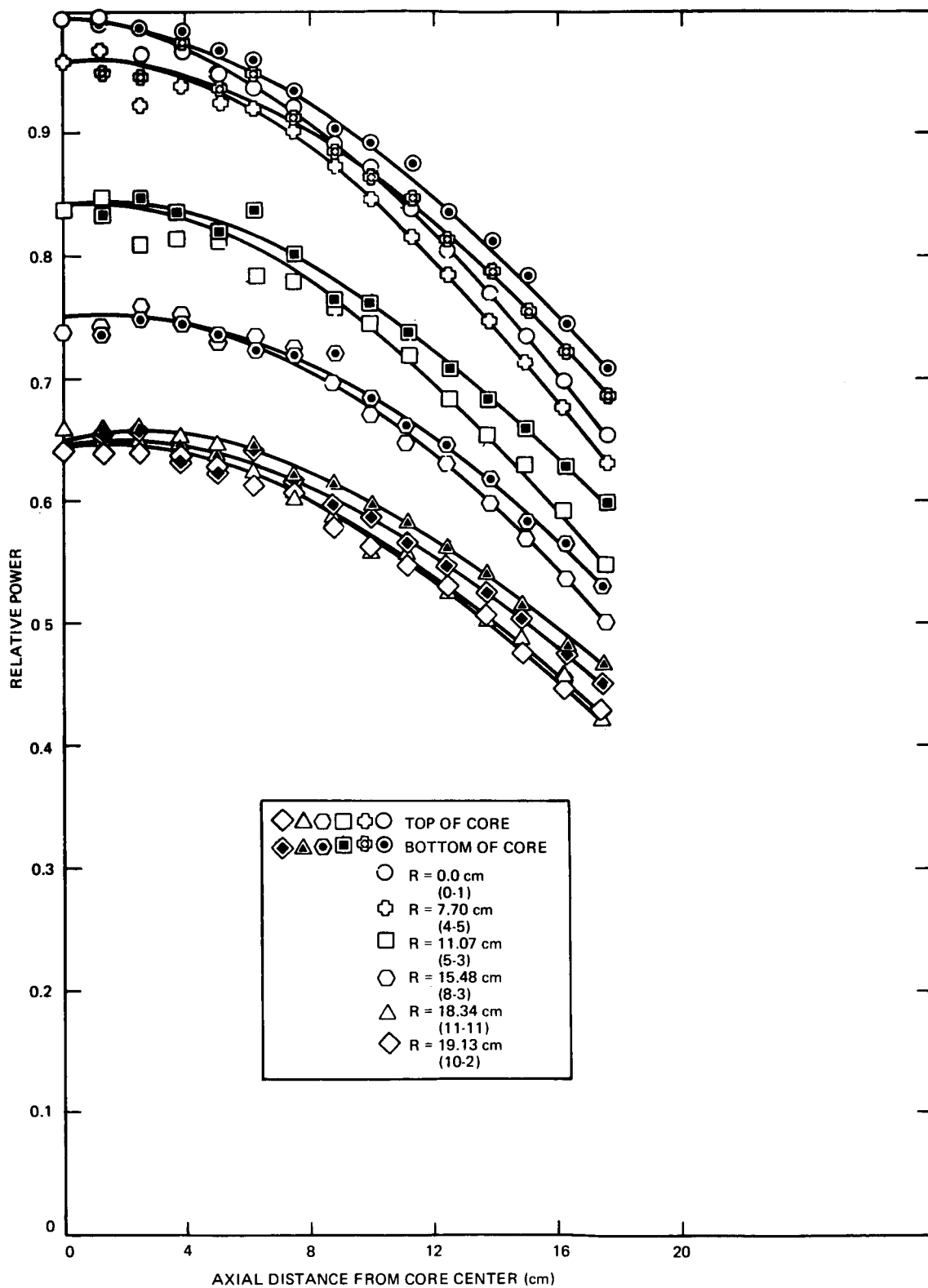
Figure 21. Axial Power Distribution (4.90-cm-long Mo Reflector)
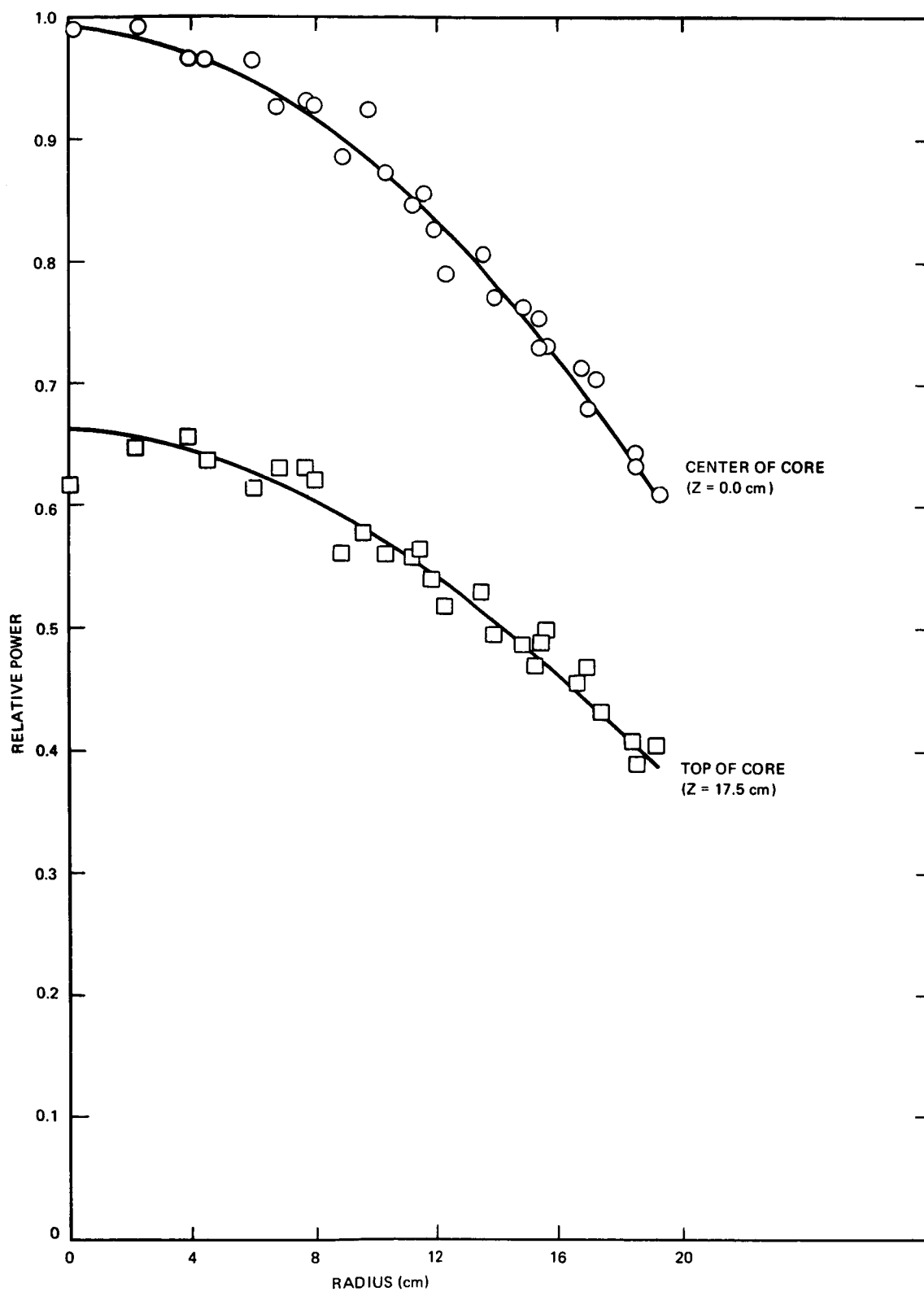
6526-4612

Figure 22. Radial Power Distribution (2.45-cm-long Mo Reflector)
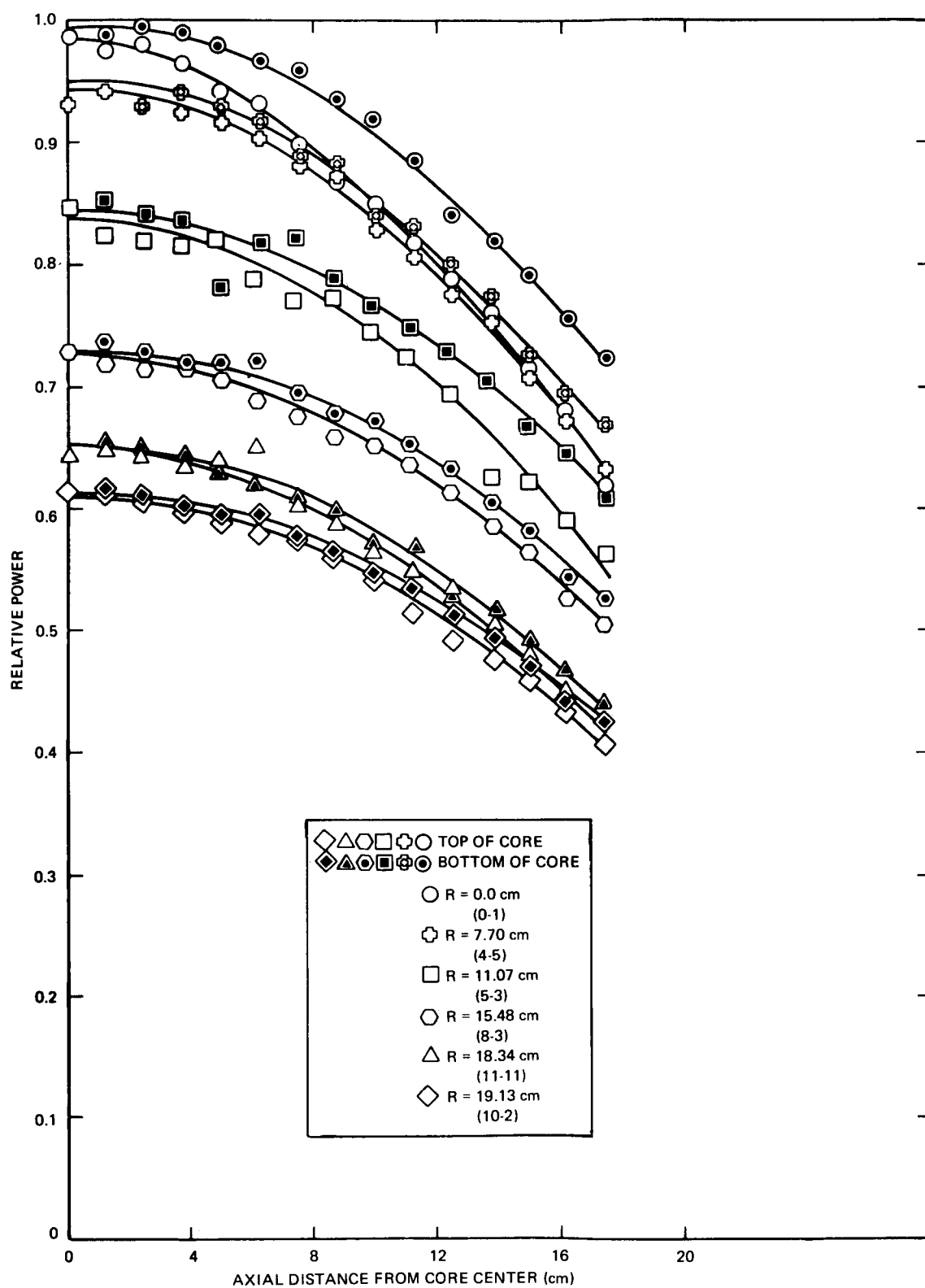
6526-4613

Figure 23. Axial Power Distribution (2.45-cm-long Mo Reflector)

RELATIVE POWER

AXIAL DISTANCE FROM CORE CENTER (cm)

◇△○□⊖○ TOP OF CORE
◆▲◉■⊕◉ BOTTOM OF CORE

○ R = 0.0 cm
    (0-1)
⊖ R = 7.70 cm
    (4-5)
□ R = 11.07 cm
    (5-3)
⬡ R = 15.48 cm
    (8-3)
△ R = 18.34 cm
    (11-11)
◇ R = 19.13 cm
    (10-2)

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NOTE: SOME ANOMALOUS VALUES ARBITRARILY
DELETED: SEE SECTION II-B-6-d

○ CENTER OF CORE (Z= 0.0 cm)
□ MIDWAY (Z = 8.75 cm)
△ TOP OF CORE (Z = 17.5 cm)
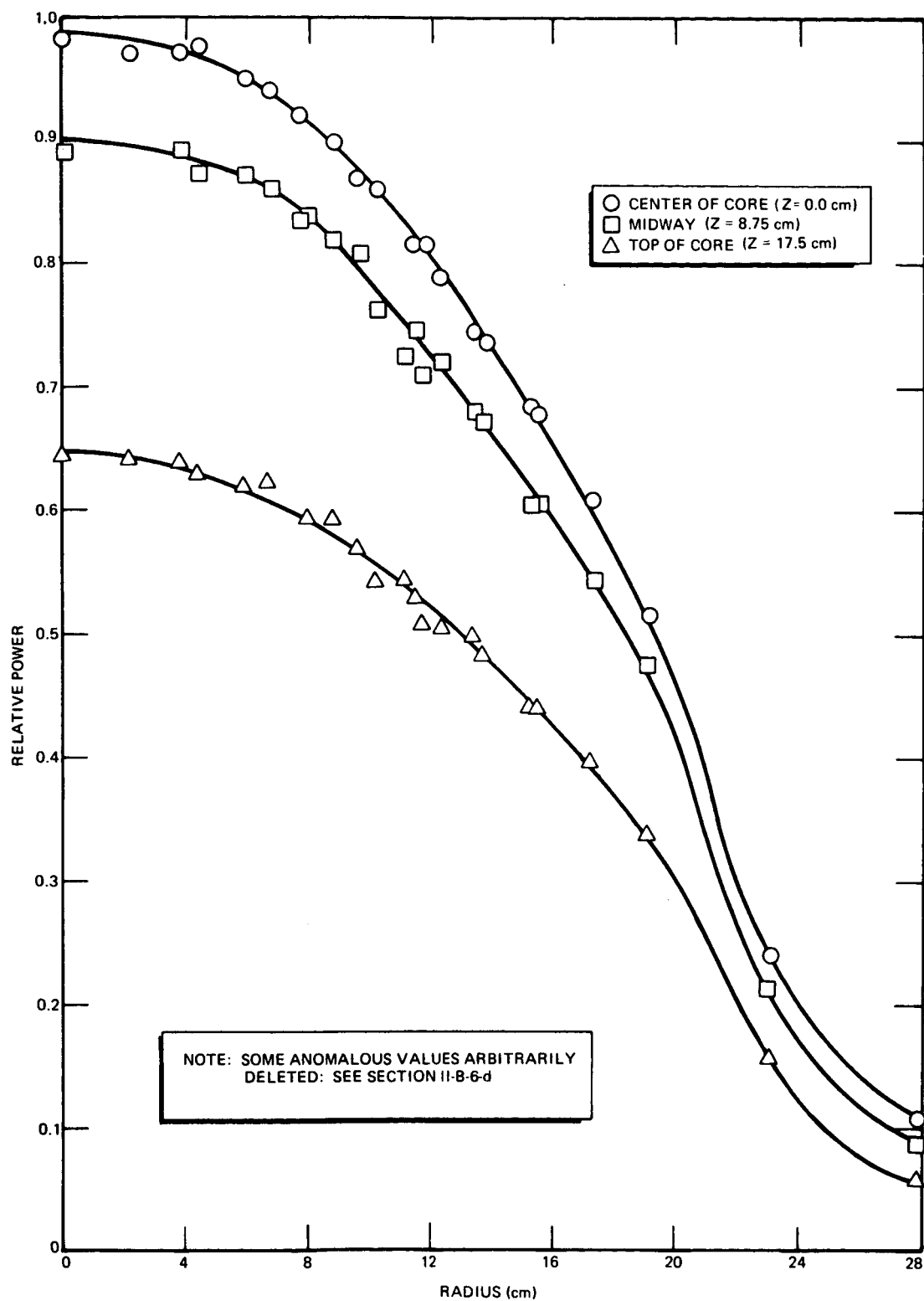
6526-4615

Figure 24. Radial Power Distribution (B$_4$C-Controlled Reactor)
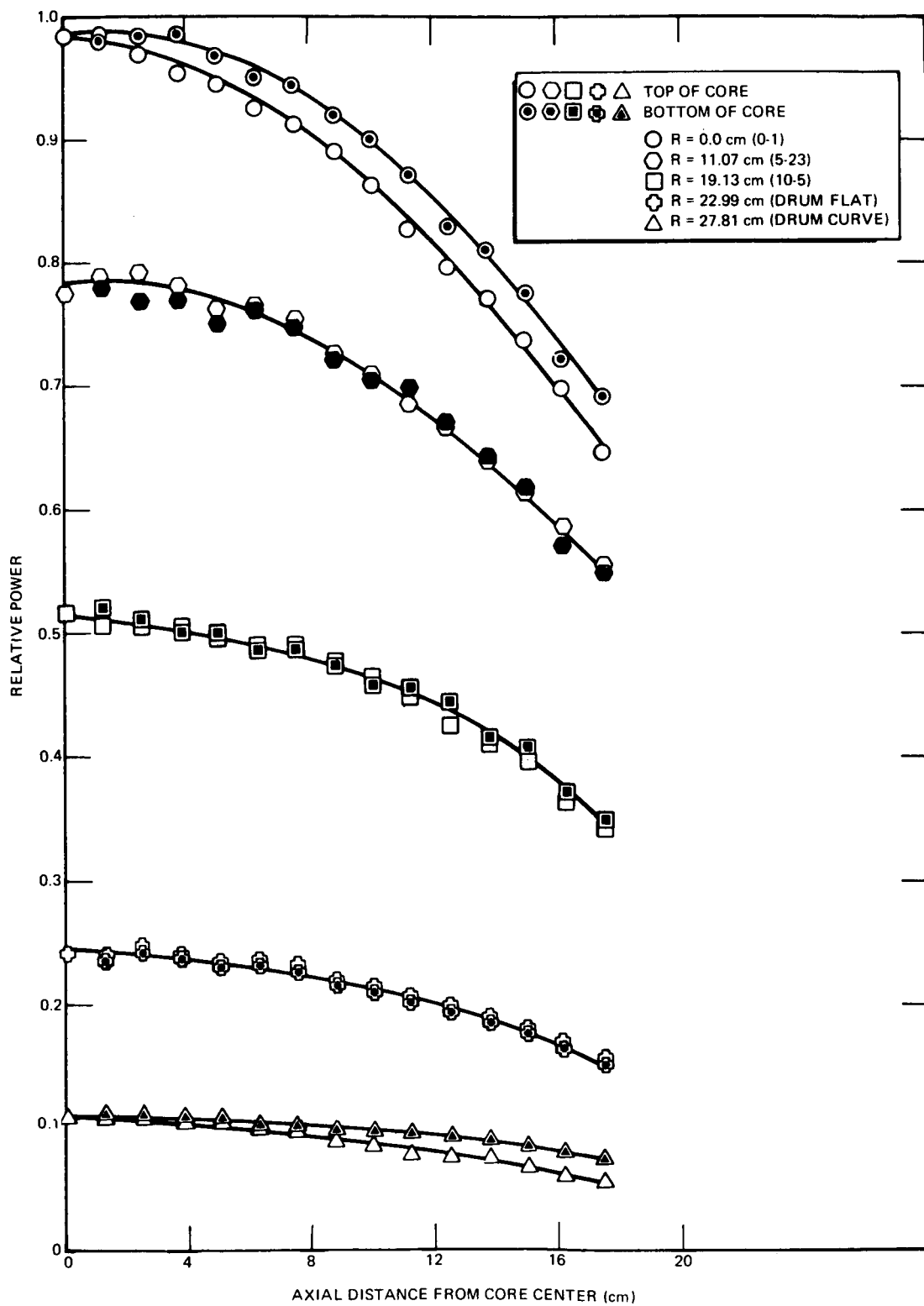
Figure 25.   Axial Power Distribution (B$_4$C-Controlled Reactor)

6526-4616

determined (only at the mid-plane and top of the core) but full-core-height distributions were made within Fuel Elements 0-1, 4-5, 5-3, 8-3, 11-11, and 10-2. In Core 5.0, power distributions were made not only in the axial and radial directions in the active core, but also at two positions within the aluminum canister containing the $B_4C$ powder in the control drum. The drum was turned during this run to its most reactive position; i. e., to a position such that the $B_4C$ sector was as far from the core axis as possible. The two uranium wires, which were irradiated, segmented, and counted to determine the power distribution, were located at the intersections of the canister walls and the plane passing through the core axis and the axis of the drum (see Section II-B).

Several axial power distributions do not exhibit symmetry about the core midplane; i. e., the power within a single fuel element tends to decrease more rapidly from the core midplane to the top of the core than from the core midplane to the bottom of the core. This phenomenon is particularly evident in Figures 21 and 23 which apply to the axial distribution in the core with one-half and one-quarter length cylindrical axial reflectors, respectively. This fact may indicate that the structural materials on which the critical assembly is placed may be reflecting neutrons back into the system.

## B. DETAILED EXPERIMENTAL RESULTS

### 1. Reactivity Worths of a Polyethylene Shield (Cores 1.1 through 1.3)

#### a. Core Description

A polyethylene shield was installed in this series of experiments around the side, top, and bottom of the three-zoned, power-flattened core as depicted in Figure 26. Each of the 73 fuel elements in Zone 1 of the reactor contained 6 uranium rods and 1 uranium wire. The average weight of the fuel in a fuel cluster in this zone was 628.47 gm, thus yielding a total uranium loading for this zone of 45.878 kg. Each of the 90 fuel elements in Zone 2 contained 7 rods and no wires, the average uranium weight per element being 717.24 gm and the total weight of uranium for the zone being 64.551 kg. Each of the remaining 84 fuel elements in Zone 3 contained 7 rods and 4 wires, the average uranium weight per element being 768.85 gm and the total weight in the zone being 64.583 kg. The total uranium fuel loading for the core was 175.012 kg. All other materials,

Figure 26.  Three-Zoned, Power-Flattened Core Loading Arrangement
Used for Polyethylene Shield Core
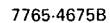
60

such as the Hf, W, and Ta foils (see Table 2) were distributed uniformly among the 247 fuel elements in the active core.

b.  Shield Description

The detailed geometric shape of the polyethylene shield was rather complex inasmuch as various clearances and cavities had to be provided for control drum motors and, particularly, for the scrammable reflector mechanism.  An overall view of the reactor with most of the shield in place is shown in Figure 27 (scrammable reflectors up) and in Figure 28 (scrammable reflectors down).

The top or upper axial shield was made up of 6 layers of polyethylene sheet each approximately 2.54 cm (1.0 in.) thick.  The laminated composite was placed on top of an aluminum deflector pan which served to prevent any polyethylene (if it should melt for any reason) from flowing into the core.  The overall height and diameter of the top shield were 17.1 cm (6.73 in.) and 89.0 cm (35.0 in.), respectively.  As can be seen in Figure 29, a top view of the polyethylene shield, six holes 10.95 cm (4.31 in.) in diameter were cut in each of the six laminations in order to provide room for the drum drive motors and housings.  The total weight of the top shield was 93.648 kg.

The radial portion of the polyethylene shield was made up of several sections, all of which extended to some degree below the lower grid plate.  Thus some parts of the shield which would normally be considered the lower axial reflector were an integral part of the radial shield.

A cross-sectional view at the core midplane is shown schematically in Figure 30.  The sections that are attached to the scrammable reflectors and therefore fall away from the core when the reactor is shut down are constructed of nominally 0.635-cm(0.250-in.)-thick sheets, thermally set to the correct curvature.  The sheets are built up to an overall radial thickness of 16.1 cm (6.34 in.), a height of about 75.1 cm (29.55 in.), and a distance along the periphery of about 113 cm (44.5 in.).  Numerous, geometrically complex cut-outs (see Figure 27) were required to avoid interference between the shield and the scrammable reflector drive motors, gear boxes, and drive mechanism mounting brackets, identical sets of which exist on both sides of the reactor.  The weight of the two radial shield sections (east and west) were 78.325 and 79.940 kg, respectively.  In order to reduce steaming through the hole in the radial shield
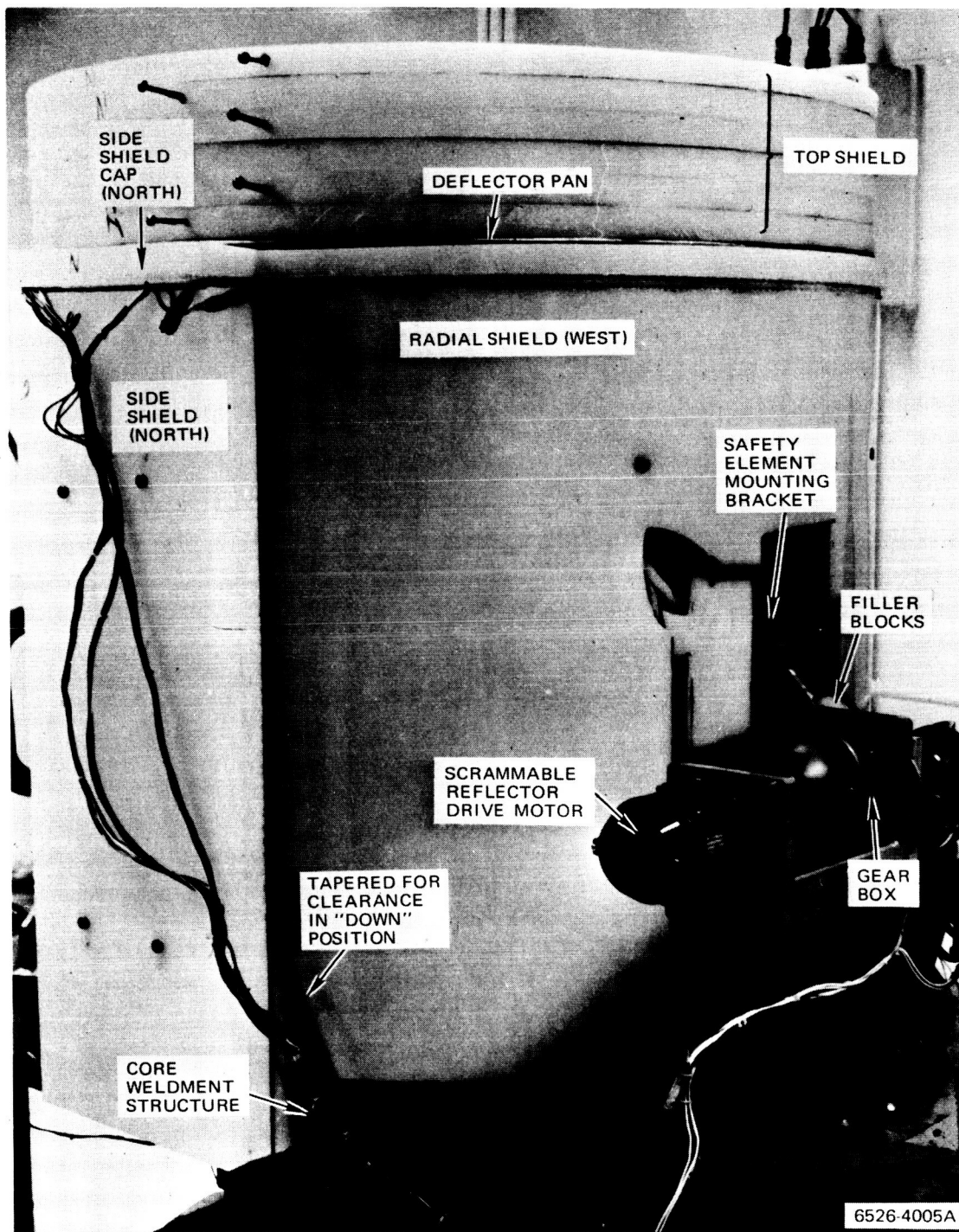
Figure 27. Polyethylene Shield with Scrammable Reflectors Up
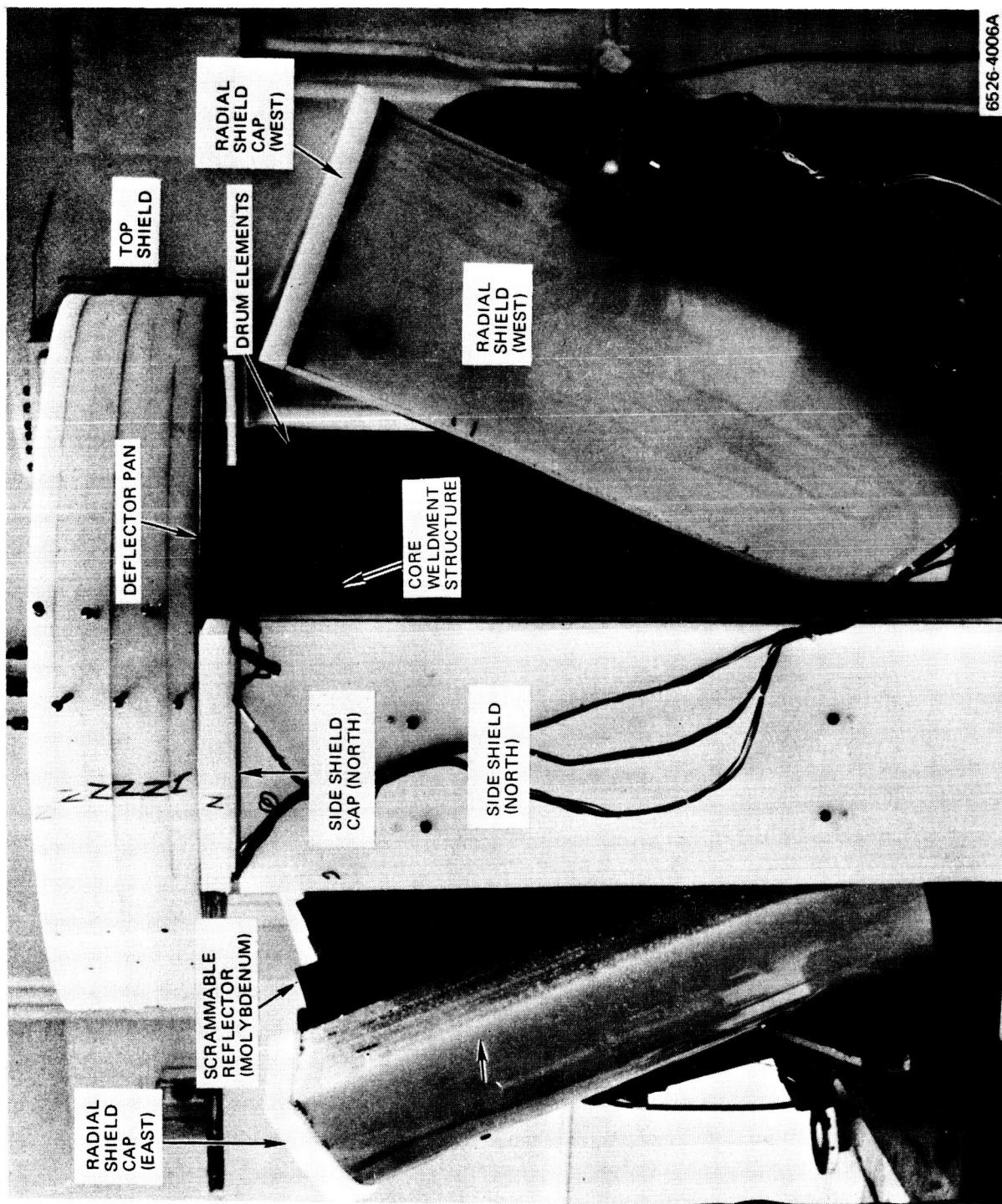
Figure 28. Polyethylene Shield with Scrammable Reflectors Down

POLYETHYLENE

HOLE FOR CONTROL DRUM DRIVE (TYP)

6526-4617

89.0 cm (DIAMETER)

10.95 cm (TYP)

60° (TYP)

18.38 cm (RADIUS)
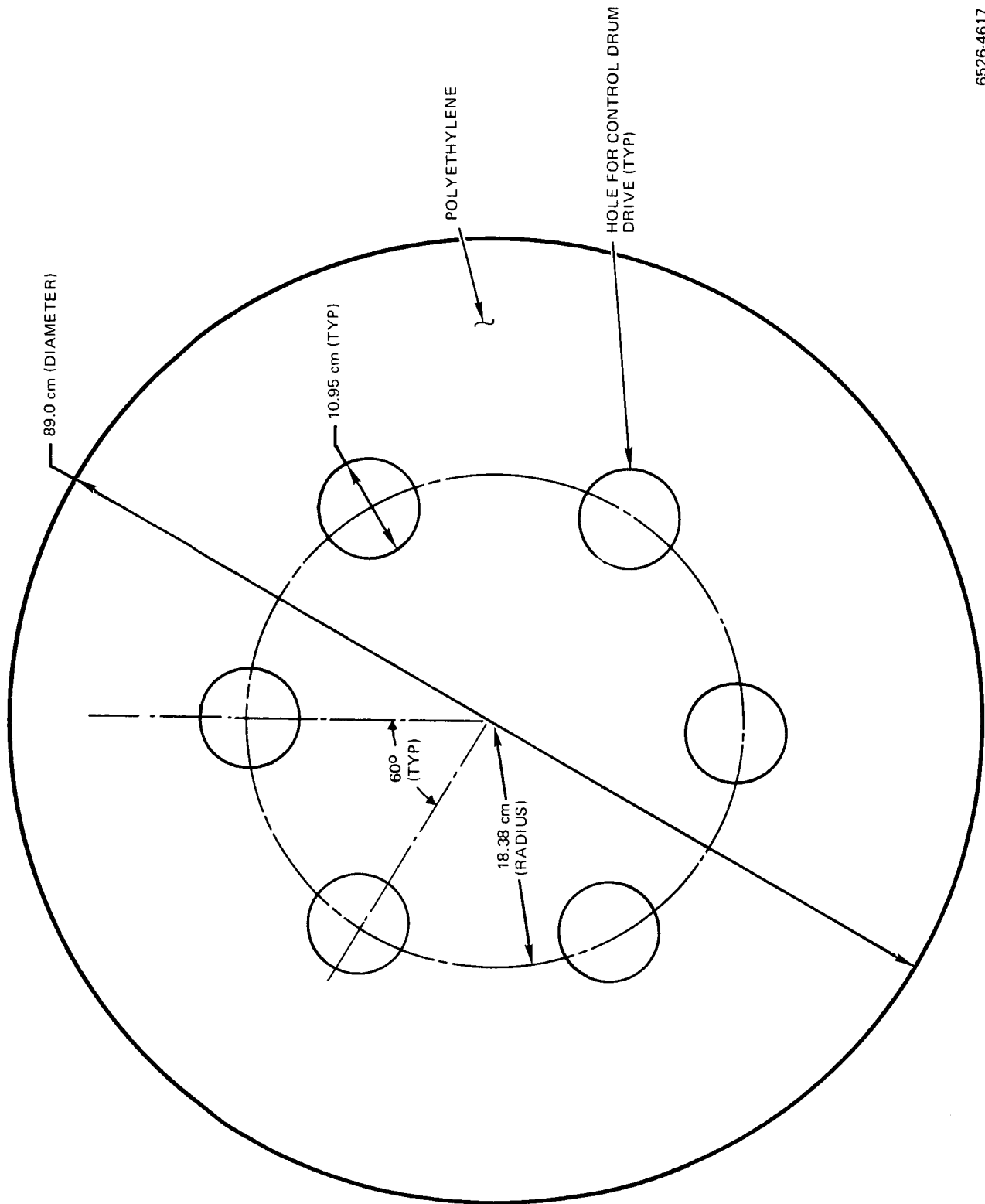
Figure 29. Polyethylene Shield – Top View Layout
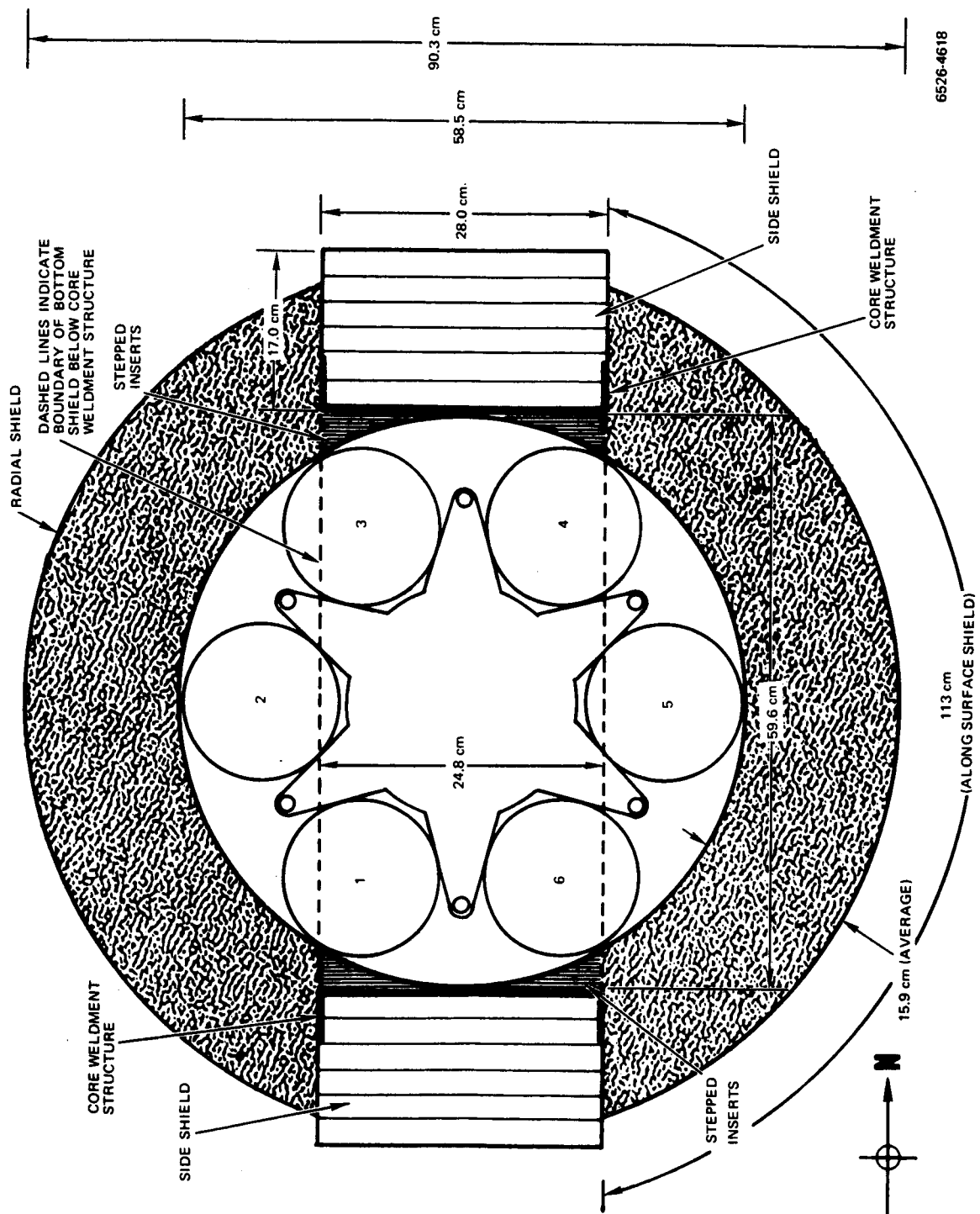
Figure 30. Polyethylene Shield — Cross Sectional View Near the Core Midplane

RADIAL SHIELD

DASHED LINES INDICATE
BOUNDARY OF BOTTOM
SHIELD BELOW CORE
WELDMENT STRUCTURE

STEPPED
INSERTS

28.0 cm.

17.0 cm

58.5 cm

90.3 cm

6526-4618

SIDE SHIELD

CORE WELDMENT
STRUCTURE

59.6 cm

113 cm
(ALONG SURFACE SHIELD)

15.9 cm (AVERAGE)

STEPPED
INSERTS

CORE WELDMENT
STRUCTURE

SIDE SHIELD

24.8 cm

N

Figure 31. Polyethylene Shield — Cross Sectional View Through Core Axis

TOP SHIELD

17.1 cm

RADIAL SHIELD CAP

RADIAL SHIELD

CORE WELDMENT STRUCTURE

CORE WELDMENT CROSS PLATE

LOWER GRID PLATE

CENTER SHIELD

CORNER BLOCKS

TAPERED FOR CLEARANCE IN "DOWN" POSITION

91.08 cm DIAMETER

SIDE SHIELD CAP

82.4 cm

24.8 cm

23.6°

SAFETY IN POSITION

3.5 cm

15.4 cm

SAFETY OUT POSITION

6526-4619

66

through which the safety element mounting bracket passes, some polyethylene blocks were constructed to fit into the inner regions of these brackets. One of these blocks, which are called filler blocks, is visible in the photograph which constitutes Figure 27. The west block weighed 1.657 kg and the east block weighed 1.594 kg.

To fill up the space that would normally exist between the core weldment structure and the core, four stepped inserts were prepared and installed as indicated in Figure 30. These inserts, each weighing 1.02 kg, were also constructed of 0.635-cm(0.250-in.)-thick polyethylene sheets and extended over the same axial height as did the reactor fuel element.

To provide polyethylene material on the two sides of the reactor on which the core weldment structure is located, sheets of normally 2.54-cm(1.0-in.)-thick polyethylene were stacked to form a 17.0-cm(6.69-in.)-thick by 28.1-cm (11.1-in.)-wide by 82.4-cm(32.44-in.)-high side shield, one on each side as depicted in Figure 30. The masses of these side shields were 32.710 and 32.751 kg for the north and south sides, respectively. As can be seen in Figures 27, 28, and 31, both of the two radial and the two side shields are capped by polyethylene blocks placed in a horizontal plane. The side shield caps one on the north and one on the south side of the assembly, are 3.5 cm (1.38 in.) high by 28 cm (11.0 in.) wide by 15.6 cm (6.14 in.) thick and weight 1.075 kg each. The radial shield caps form an integral part of the radial shield and are included in the total mass for the latter.

The lower axial shield, which, under ideal circumstances, should be a right circular cylinder similar to the upper axial shield and independently removable, is actually made up of two types of polyethylene components. One component is a nonseparable part of the radial shield system in whose total mass it is included and the other a collection of special shapes fitted into the available space below the lower grid plate of the reactor. The material making up the radial shield was designed to extend below the lower grid plate in order to avoid various mechanical and safety problems associated with the fall-away reflector system. However, reference to Figures 27 and 31 shows that the lower parts of the radial shield had to be chamfered in order to allow clearance for these safety mechanisms. These chamfers resulted in a loss of shield material that could not be avoided without major alterations in the reactor structure.

TABLE 6

POLYETHYLENE SHIELD DATA

| Item | Dimensional Description (cm)* | Weights of Integral Section (kg) | |
|---|---|---|---|
| Top Shield | 17.1 high, 89.0 diameter, 6 holes each 11.0 diameter | 84.749 | 84.749 |
| Radial Shield (East) | 16.1 thick, 112.6 along outer periphery, 75.1 high (maximum) | 78.325 | |
| Radial Shield (West) | 16.1 thick, 113.2 along outer periphery, 74.7 high (maximum) | 79.940 | |
| Radial Shield Cap (East) | 3.4 high, 16.1 thick | 4.441 | |
| Radial Shield Cap (West) | 3.5 high, 16.1 thick | 4.458 | |
| Side Shield (North) | 17.1 thick, 28.0 wide, 82.3 high | 32.710 | 242.106 |
| Side Shield (South) | 16.9 thick, 28.2 wide, 82.5 high | 32.751 | |
| Side Shield Cap (North) | 15.8 thick, 28.0 wide, 3.5 high | 1.075 | |
| Side Shield Cap (South) | 15.4 thick, 27.8 wide, 3.5 high | 1.075 | |
| Stepped Inserts (4) | 2.54 thick (maximum), 10.0 wide (maximum), 82.4 high | 4.08 | |
| Filler Block (West) | 4.6 thick | 1.657 | |
| Filler Block (East) | 4.6 thick | 1.594 | |
| Center Shield | 15.4 high, 24.8 wide, 59.6 thick | 20.975 | 25.835 |
| Corner Blocks (4) | 15.4 high | 4.860 | |

*Width dimensions apply to straight line distances in horizontal plane and perpendicular to radial distances ($\theta$ direction). Height dimensions apply to vertical distances parallel to the axis of the core (z direction). Thickness dimensions apply to radial distances in horizontal planes (r direction).

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The special shapes that make up a portion of the lower shield and that are readily removable are called corner blocks (of which there are four) and the center shield. The center shield is placed directly below the core weldment structure cross member (see Figures 30 and 31) and is 15.4 cm (6.06 in. ) high by 24.8 cm (9.8 in. ) wide by 59.6 cm (23.5 in. ) long. It is made up of nominally 2.54-cm(1.0-in. )-thick polyethylene sheets stacked together, and weighs, in total, 20.975 kg. The corner blocks are odd-shaped pieces of polyethylene that, in one cross section, look approximately like the structure shown in Figure 31. One block is located below each of the spaces between Drums 1 and 2, 2 and 3, 4 and 5, and 5 and 6. They weigh 1.215 kg each.

A summary of the polyethylene shield data is given in Table 6. The poly-ethylene material from which the shield was constructed was purchased in sheet form and conforms to Federal Specification L-P-390, Type 2, low density (0.910 to 0.925 $gm/cm^3$). Chemical analyses were conducted on representative samples of the sheets and are reported in Appendix A.

c. Reactivity Worth of Shields

After the full polyethylene shield, as described above, was installed around the core structure, groups of fuel elements, already loaded with fuel in accord-ance with the 3-zoned configuration, were placed in the reactor and a standard 1/M approach-to-critical was carried out. A $Cf^{252}$ source was placed at the center of the core and, before loading began, was used to establish a back-ground neutron count rate. For this series of experiments, three of the six neutron detectors (Channels 2, 3, and 4) were placed on top of the top shield. The remaining three detectors (Channels 1, 5, and 6) were placed on the sample changer table which was 23.5 cm (9.3 in. ) below the bottom surface of the table on which the reactor is mounted (see Figure 1). Neutron count levels were measured after the core was loaded with 66, 155, 200, 223, 234, 240, 242, and 243 fuel elements. With 243 fuel elements in place, the reactor was still sub-critical. Elements in Positions 7-6, 9-12, 8-6, and 0-1 were absent. As these elements were added, one at a time and in the order listed, the excess reactiv-ity assumed values of 16, 49, 69, and 137¢ respectively.

A drum calibration (see Figure 10) was performed and established that the total excess reactivity that would exist if all drums were driven to the fuel-full-in position would be 136.7¢. This value represents the total excess available in

the three-zoned, power-flattened core with a complete polyethylene shield in place (Core 1.1).

To obtain the reactivity effects of the top and bottom polyethylene shield relative to the total shield worth, an intermediate excess reactivity measurement was obtained before the entire shield was removed. Of the total polyethylene mass of 352.668 kg making up the full shield, 110.584 kg were removed. Of this 110.584 kg, 84.749 kg represented the top shield and 25.835 kg represented the removable portion of the bottom shield; i.e., the center shield and the corner blocks. The all-drums-in excess reactivity of the reactor with the 110.584 kg of polyethylene removed was 121.1¢ (Core 1.2), thus indicating that the "axial" shields are worth 15.6¢.

All of the polyethylene shield material was removed from the reactor and the all-drums-in excess reactivity was again measured with the standard polyethylene boxes situated around the six detectors which had been returned to the positions indicated in Figure 8. The value of the excess reactivity was found to be 44.6¢, which, when corrected for the worth of the polyethylene boxes, yielded a net excess of 30.6¢ (Core 1.0). The net worth of the fuel shield was therefore 106.1¢.

d. Control Characteristics of the Polythylene Shielded Core (Core 1.1)

With the full polyethylene shield in place, a series of drum calibrations was performed to establish the reactivity control inherent in each of the six drums driven individually. A calibration by the step-wise technique was carried out on each drum out to about 90° of arc, whereupon a continuous drive to full-out (180°) was performed. A typical worth curve was shown in Figure 10. The total control swings measured for Drums 1, 2, 3, 4, 5, and 6, taken individually, were 235.2, 239.1, 234.4, 234.9, 240.5, and 234.3¢, respectively.

To measure the worth of all drums ganged by the inverse counting technique, the central fuel element in Position 0-1 was removed and a $Cf^{252}$ source was placed at the core center. The fuel loading in each element in Positions 1-1 through 1-6, inclusive, was reduced to 5 rods each of the 0.432-cm(0.170-in.)-diam U in order to reduce the total excess to less than 40¢. The inverse counting was performed with all rods banked to 23, 28, 40, 60, 80, 100, 120, 140,

160, and 175°. Counting data were recorded by Channels 1, 2, and 6 which were located as shown in Figure 8. The total worth was found to be $15.36 which represents the average worth as determined by two channels and two normalization points (23° and 28°). A plot of the data from Channel 6 normalized at 23° is given in Figure 32. The average worth of a single drum is about $2.36; consequently, if no interaction takes place, the total worth would be expected to be $14.18.

e. The Power Distribution in the Polyethylene Shielded Core (Core 1.2)

The power distribution in a one-twelfth sector of the three-zoned, power-flattened core was measured with the full polyethylene shield in place. Twenty-seven uranium wires each 0.066 cm (0.026 in.) in diameter were placed in the one-twelfth sector defined by the plane passing through the axis of the core and the axis of the fuel element in Position 10-2, and by the plane passing through the axis of the core and the axis of the fuel element in Position 5-3 (see Figure 33). Control Drums 1, 2, 4, and 5 were in the fuel-full-in position whereas Control Drums 3 and 6 were banked to 54°10' in order to maintain level power. After irradiation, one wire segment about 1.27 cm (0.5 in.) long was cut from the top, from the center, and from a point halfway in between each of the 27 wires. The uranium wires in fuel elements in Positions 0-1, 10-2, 5-3, and 11-11 were completely segmented and counted over their entire lengths. The results of this experiment were previously given in Figures 19 and 20 and are tabulated in Tables 7 and 8.

2. The Neutron Spectrum at the Core-Reflector Interface

a. Core Description

Upon completion of the studies pertaining to the polyethylene shield, the fuel elements in the three-zoned, power-flattened core were removed along with the shield, and the fuel cluster was disassembled. In preparation for the proton-recoil spectrometer measurements at the upper core-reflector interface, a fuel cluster consisting of 6 of the 0.432-cm(0.170-in.)-diam uranium rods and 7 of the 0.152-cm(0.060-in.)-diam uranium wires was formed and placed in each of the 247 fuel elements. All W, Hf, and Ta foil was removed as shown in Table 2.

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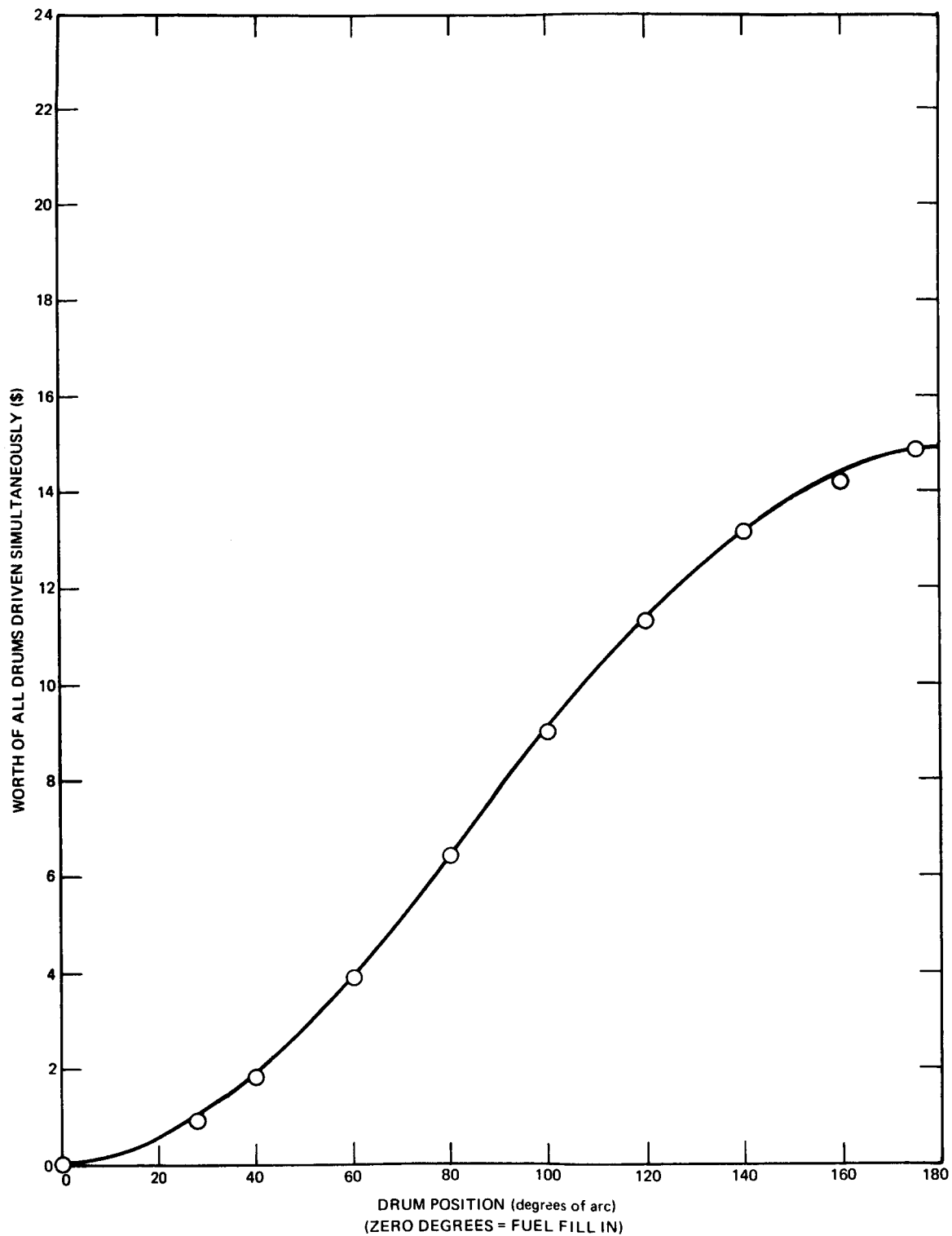
Figure 32. Reactivity Worth of All Drums Ganged
Polyethylene Shielded Core

6526-4620

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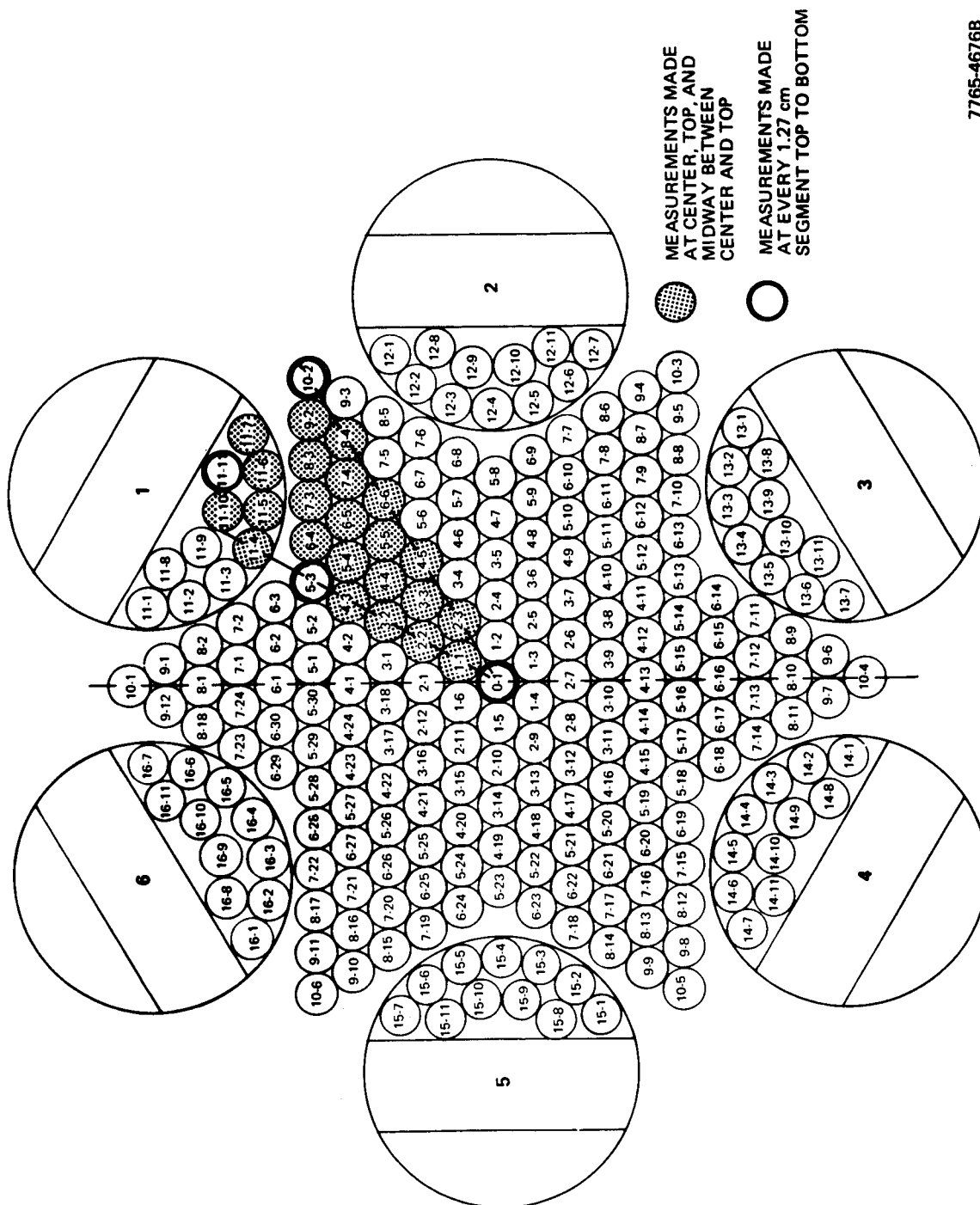
Figure 33.   Power Distribution Wire Loading Scheme
Polytheylene Shielded Core

MEASUREMENTS MADE
AT CENTER, TOP, AND
MIDWAY BETWEEN
CENTER AND TOP

MEASUREMENTS MADE
AT EVERY 1.27 cm
SEGMENT TOP TO BOTTOM

7765-4676B

73

TABLE 7

RADIAL POWER DISTRIBUTION
(Polyethylene Shielded Core)
RELATIVE POWER

| Wire Segment Number | Radius (cm) | Fuel Element Number | Center (z = 0.0 cm) | Midway (z = 8.89 cm) | Top (z = 17.78 cm) |
|---|---|---|---|---|---|
| 1 | 0 | 0-1 | 0.987 | 0.908 | 0.690 |
| 2 | 2.18 | 1-1 | 0.976 | 0.914 | 0.713 |
| 3 | 3.85 | 2-3 | 0.983 | 0.889 | 0.658 |
| 4 | 4.40 | 2-2 | 0.961 | 0.877 | 0.662 |
| 5 | 5.87 | 3-3 | 0.960 | 0.874 | 0.651 |
| 6 | 6.67 | 3-2 | 0.947 | 0.866 | 0.635 |
| 7 | 7.70 | 4-5 | 0.911 | 0.841 | 0.629 |
| 8 | 7.98 | 4-4 | 0.918 | 0.850 | 0.633 |
| 9 | 8.85 | 4-3 | 0.915 | 0.838 | 0.616 |
| 10 | 9.64 | 5-5 | 0.888 | 0.817 | 0.618 |
| 11 | 9.99 | 5-4 | 0.868 | 0.793 | 0.611 |
| 12 | 11.07 | 5-3 | 0.862 | 0.797 | 0.605 |
| 13 | 11.47 | 6-6 | 0.821 | 0.769 | 0.577 |
| 14 | 11.75 | 6-5 | 0.839 | 0.770 | 0.560 |
| 15 | 12.36 | 6-4 | 0.812 | 0.743 | 0.545 |
| 16 | 13.56 | 7-4 | 0.817 | 0.722 | 0.528 |
| 17 | 13.83 | 7-3 | 0.776 | 0.709 | 0.530 |
| 18 | 14.55 | 11-5 | 0.775 | 0.699 | 0.527 |
| 19 | 14.68 | 11-4 | 0.769 | 0.704 | 0.515 |
| 20 | 15.28 | 8-4 | 0.684 | 0.673 | 0.521 |
| 21 | 15.42 | 8-3 | 0.743 | 0.673 | 0.515 |
| 22 | 16.65 | 11-6 | 0.695 | 0.631 | 0.499 |
| 23 | 17.15 | 9-2 | 0.749 | 0.643 | 0.490 |
| 24 | 17.35 | 11-10 | 0.686 | 0.641 | 0.457 |
| 25 | 18.80 | 11-11 | 0.645 | 0.588 | 0.434 |
| 26 | 19.07 | 10-2 | 0.635 | 0.579 | 0.434 |
| 27 | 19.18 | 11-7 | 0.649 | 0.592 | 0.445 |

## TABLE 8
### AXIAL POWER DISTRIBUTION
(Polyethylene Shielded Core)
### RELATIVE POWER

| Wire Segment Number | Distance From Core Center (cm) | 0-1 (R = 0.0 cm) | 5-3 (R = 11.07 cm) | 11-11 (R = 18.80 cm) | 10-2 (R = 19.07 cm) |
|---|---|---|---|---|---|
| Top | | | | | |
| 1 | 17.78 | 0.690 | 0.605 | 0.434 | 0.434 |
| 2 | 16.56 | 0.719 | 0.632 | 0.456 | 0.456 |
| 3 | 15.34 | 0.759 | 0.672 | 0.482 | 0.466 |
| 4 | 14.11 | 0.788 | 0.688 | 0.508 | 0.502 |
| 5 | 12.89 | 0.824 | 0.706 | 0.528 | 0.522 |
| 6 | 11.67 | 0.852 | 0.743 | 0.544 | 0.531 |
| 7 | 10.45 | 0.875 | 0.769 | 0.559 | 0.550 |
| 8 | 9.23 | 0.898 | 0.787 | 0.584 | 0.578 |
| 9 | 8.00 | 0.928 | 0.798 | 0.600 | 0.592 |
| 10 | 6.78 | 0.937 | 0.830 | 0.610 | 0.604 |
| 11 | 5.56 | 0.954 | 0.843 | 0.615 | 0.603 |
| 12 | 4.34 | 0.977 | 0.85 | 0.628 | 0.613 |
| 13 | 3.12 | 0.975 | 0.839 | 0.645 | 0.634 |
| 14 | 1.90 | 0.993 | 0.861 | 0.642 | 0.622 |
| 15 | 0.67 | 0.997 | 0.857 | 0.644 | 0.639 |
| 16 | -0.55 | 0.978 | 0.868 | 0.644 | 0.633 |
| 17 | -1.77 | 0.971 | 0.862 | 0.644 | 0.646 |
| 18 | -2.99 | 0.987 | 0.866 | 0.650 | 0.638 |
| 19 | -4.21 | 0.970 | 0.847 | 0.647 | 0.628 |
| 20 | -5.44 | 0.957 | 0.848 | 0.629 | 0.612 |
| 21 | -6.66 | 0.949 | 0.837 | 0.621 | 0.609 |
| 22 | -7.88 | 0.946 | 0.816 | 0.616 | 0.596 |
| 23 | -9.10 | 0.932 | 0.795 | 0.604 | 0.592 |
| 24 | -10.32 | 0.907 | 0.785 | 0.582 | 0.570 |
| 25 | -11.55 | 0.863 | 0.760 | 0.570 | 0.556 |
| 26 | -12.77 | 0.847 | 0.722 | 0.549 | 0.539 |
| 27 | -13.99 | 0.811 | 0.704 | 0.528 | 0.532 |
| 28 | -15.21 | 0.799 | 0.680 | 0.492 | 0.493 |
| 29 | -16.43 | 0.741 | 0.654 | 0.474 | 0.470 |
| 30 | -17.66 | 0.721 | 0.609 | 0.449 | 0.441 |
| Bottom | | | | | |

HONEYCOMB TUBE WITH INTERNAL MOLYBDENUM REFLECTOR SEGMENTS

HONEYCOMB TUBE WITH MOLYBDENUM FOIL INSIDE

HIGH-VOLTAGE AND SIGNAL LEAD

6526-4009A

T-111 SPACER SLEEVE

SPHERICAL PROTON-RECOIL DETECTOR

SPACER ELEMENTS

FUEL ELEMENT ALIGNMENT PINS

"PROTON-RECOIL" FUEL ELEMENTS

TANTALUM PLUGS
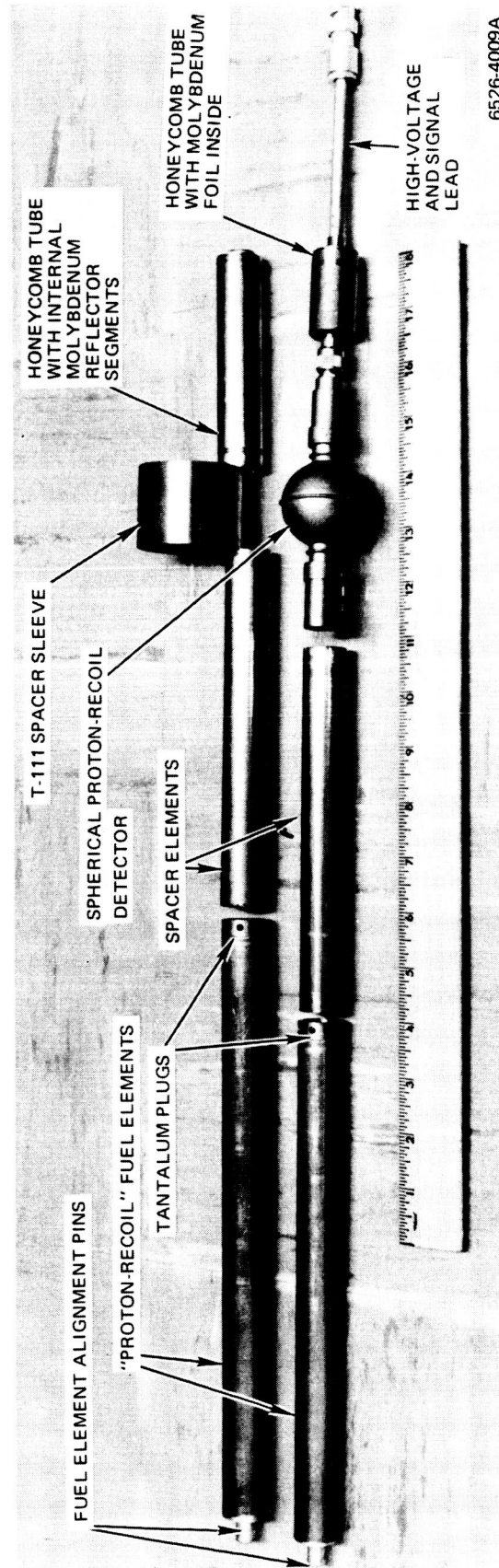
Figure 34. Proton-Recoil Detector Arrangement – Layout View

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The total weight of fuel in all elements was 174.991 kg with an average weight per element of 708.46 gm. The absolute spread in mass was less than or equal to ±1.2 gm.

To install the spherical proton-recoil detector in the core, the central seven fuel elements (0-1, and 1-1 through 1-6, inclusive) were removed from the reactor. In these seven positions and at the bottom of the reactor were placed seven short elements that contain all of the core materials, including $Li_3^7N$, that would normally be installed in a standard fuel element. These special elements, which are described in detail in Appendix C of Reference 1, contain a 15.24-cm(6.0-in.)-long fuel cluster and are sealed in the top of a Ta plug as shown in Figure 34. On top of these so-called "proton-recoil" fuel elements, were placed six special spacer elements, each of which consisted of a 17.02-cm(6.7-in.)-long Ta honeycomb tube into which was placed a 17.02-cm (6.7-in.)-long Ta fuel tube and a 15.24-cm(6.0-in.)-long fuel cluster. The Ta fuel tube was located concentrically within the honeycomb tube by means of an annular-shaped Ta foil that was tack-welded into place as shown in Figure 35. These spacer elements served to located the proton-recoil detector in such a way that the top of the spherical active counting volume was tangent to the plane that defines the interface between the top of the active core and the bottom of the top axial reflector zone (see Figure 36). On top of the T-111 spacer sleeve, that surrounds the proton recoil detector and which rests on top of the spacer elements, are located six standard axial reflector segments. Short lengths, 10.00 cm (3.94 in.), of Ta honeycomb and fuel tubes are used with each reflector segment so that the standard core configuration is maintained above the detector. A special small-diameter 0.635-cm(0.25-in.)-high-voltage-signal lead was fabricated. A foil of Mo metal was wrapped around the lead to form a tube about 3.8 cm (1.5 in.) high with an OD of 2.11 cm (0.83 in.) and an ID of 0.64 cm (0.250 in.). A 3.81-cm(1.5-in.)-long section of Ta honeycomb tube was placed around the coil.

b.  Spectrum Measurements

With the above-described arrangement of materials and detector, a series of proton-recoil spectrum measurements was carried out using the experimental technique described at the beginning of this report. The spectrum, which is plotted in Figure 37, covered the energy range from about 40 kev to 2.3 Mev.
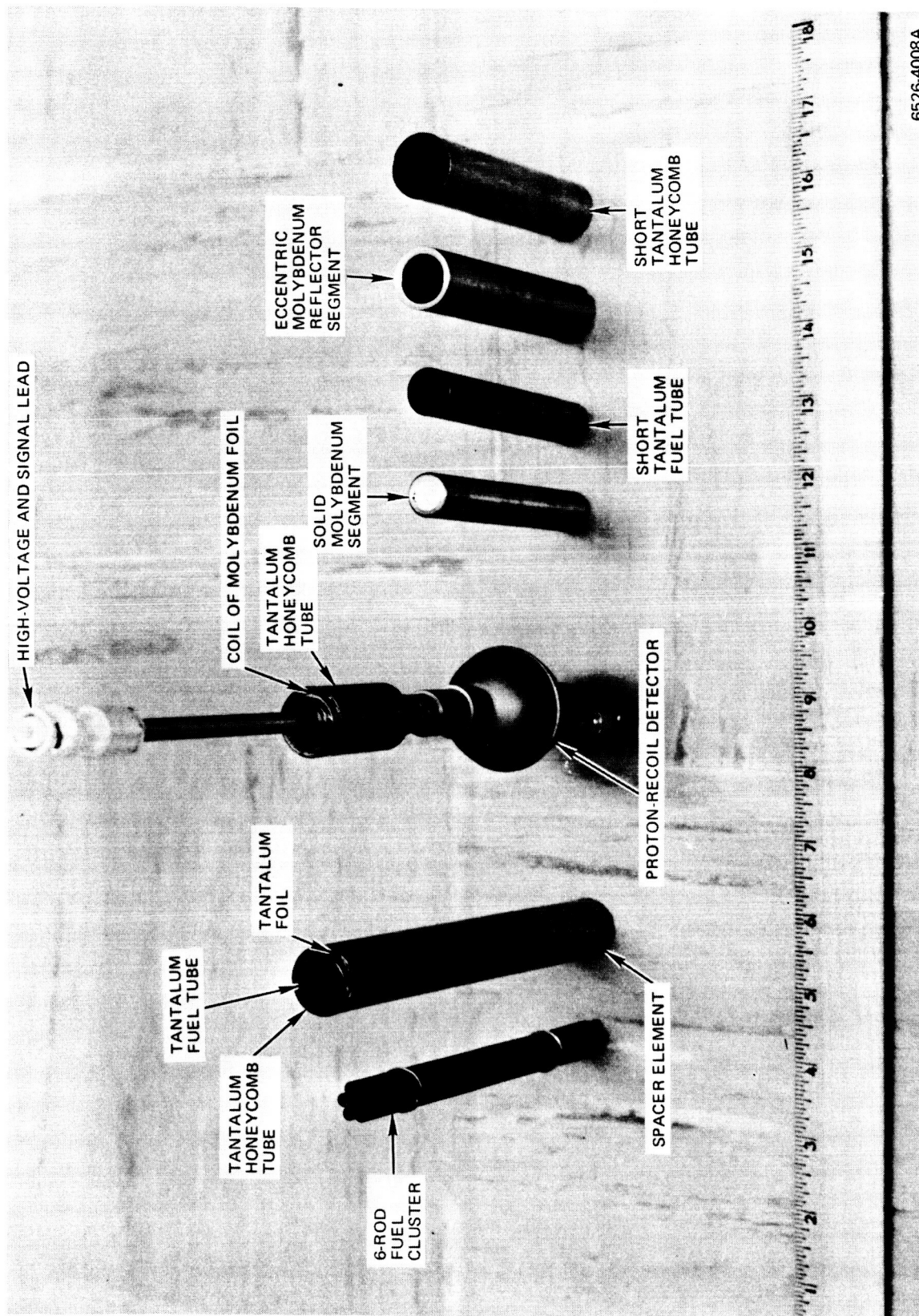
Figure 35. Proton-Recoil Detector Arrangement — Component Parts

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HIGH-VOLTAGE AND
SIGNAL LEAD

TEFLON INSULATOR

SPECIAL BRACKET

MOLYBDENUM FOIL

3.81 cm

10.00 cm

Mo REFLECTOR

REFLECTOR-CORE INTERFACE

1.91 cm    DETECTOR
                ₵
1.91 cm

FILLING TUBE

T-111 SPACER

TANTALUM FOIL

TANTALUM
HONEYCOMB
TUBE

FUEL ELEMENT HEIGHT
60.139 ± 0.0254
(23.677 ± 0.010)

16.26 cm

TANTALUM
FUEL TUBE

PROTON-RECOIL
DETECTOR

REACTOR
     ₵

SPACER FUEL ELEMENTS

STANDARD FUEL ELEMENTS

30.07 cm

SPECIAL "PROTON RECOIL" FUEL ELEMENTS

₵

ADAPTOR PLUG (TYP)

ᴜᴄ 26-4621

Figure 36.  Proton-Recoil Detector Arrangement
Schematic

79
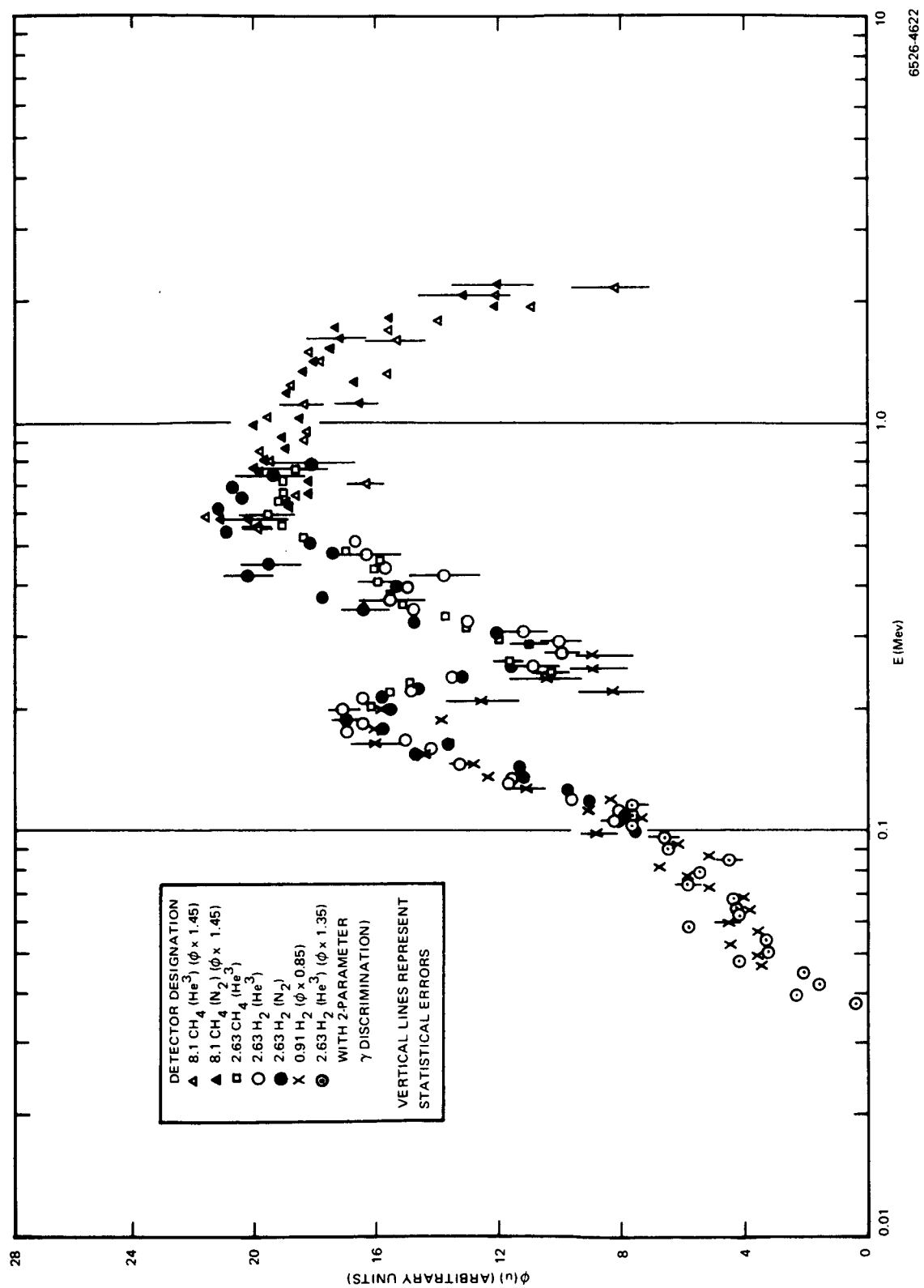
Figure 37. Neutron Spectrum at the Core-Reflector Interface

6526-4622

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Normalization factors of 1.45, 0.85, and 1.35 were applied to the data obtained from detectors designated 8.1 CH, 0.91 $H_2$, and 2.63 $H_2$, respectively. The results from the latter detector were analyzed by 2-parameter techniques. In order to verify that the different energy calibration gases do not deleteriously affect the derived spectra, duplicate measurements were made and analyzed using two different detectors with the same primary detector gas and gas pressure but with different calibration gases. As can be seen in the figure, no significant discrepancies occurred. The numerical value in each of the detector designations refers to the pressure of the filling gas in atmospheres. The values of 8.1, 2.63, and 0.91 atm are equivalent to $8.20 \times 10^5$, $2.66 \times 10^5$, and $0.92 \times 10^5$ neutrons/$m^2$, respectively.

## 3. The Reactivity Worth of Ta (Cores 2.0 and 2.1)

### a. Core Description

Upon completion of the proton-recoil spectrometer investigations, the standard fuel elements were returned to their normal locations in Positions 0-1 through 1-6, inclusive. Some fuel adjustments were made in the core to facilitate a uniform withdrawal of U wire during later phases of the program. The total mass of uranium in the re-established core was 174.88334 kg and was uniformly distributed such that the weight of fuel in any element did not differ from the average by more than ±1.2 gm. The data pertaining to the mass of non-fuel materials in the core were presented in Tables 1 and 2. The total quantity of Ta in the active core was 49.01 kg. This core, which represents the base case for Ta wire addition, was designated Core 2.0.

### b. Reactivity Worths

The objective of this series of experiments was to determine the reactivity effect of adding, in a uniform manner, an additional 9.54 kg of Ta in the form of wire to the 49.01 kg already present. The all-drums-in excess reactivity for the base case was initially determined to be 168.5¢. Inasmuch as the addition of one Ta wire, 0.279 cm (0.110 in.) in diameter by 36.83 cm (14.5 in.) long, in each of 247 fuel elements was expected on the basis of previous work to decrease the system reactivity by about 16¢, a reactivity measurement at a drum position (in this case, 113°0′) that would produce a positive reactor period corresponding

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to an insertion of about this amount was made. A new measurement at this drum position could then be made after the Ta was added and could be used to obtain a more accurate measurement of the Ta worth than would be possible on the basis of drum calibration curves alone. For Core 2.0 and Drum No. 6 at 113°0' (all other drums full-in), a positive period corresponding to an excess of 15.5¢ was observed. For Core 2.1 which corresponds to 2.0 except that the Ta has been added, the reactivity-vs-time behavior with Drum No. 6 at 113°0' (all other drums full-in) yielded a reactivity value of -1.8¢. Thus, the reactivity worth of 9.54 kg of Ta was determined to be -17.3¢. The value of -19¢, as obtained by the differences in the all-drums-in excess reactivity values for Cores 2.0 and 2.1, is in reasonably good agreement with this result.

An estimate of the critical masses of these two cores can be made using a conversion factor (50.6¢/kg) derived for a nearly identical core described in Reference 1, p. 133. If this is done, critical mass values of 171.55 and 171.93 kg are obtained. A drum calibration curve from fuel full-in to fuel full-out was determined for Core 2.0 and from fuel full-in to 115 degrees of arc for Core 2.1. These results were previously shown in Figures 11 and 12.

4. Axial Reflector Worths (Cores 3.0, 3.1, 3.2 and 3.3)

a. Reactivity Data Pertaining to a Core with 9.80-cm(3.86-in.)-long Cylindrical Mo Reflector Components at One End

The 247 Ta wires were removed from the fuel elements in Core 2.1 along with the 247 cylindrical Mo reflector components located at the bottom of the fuel elements (see Figure 6). Each of these cylindrical Mo reflector components was segmented into three lengths, one 4.90 cm (1.93 in.) long and two each 2.45 cm (0.96 in.) long. In order to ascertain the reactivity change associated with the loss of Mo in the saw-cut, each fuel element was reassembled with three short segments placed end-to-end at the bottom of the element in order to form a reflector 9.80 cm (3.86 in.) high. This height is to be compared to the 10.00-cm(3.94-in.) value for the standard reflector. With the standard reflector on the other end of the fuel element, the all-drums-in excess reactivity was determined to be 160.1¢ (Core 3.0). Similarly, Core 2.0 was identical to Core 3.0 in all respects except that the reflector at one end was shortened to 9.80 cm in the latter case. A comparison of the two all-drums-in excess reactivity

values can be made in order to evaluate the reactivity effect of losing 0.20 cm of Mo. The difference between the two values is -8.4¢. All 247 full-length solid Mo segments that constituted a portion of the upper reflector weighed 44.20 kg, whereas the stacks of three short segments that constituted a portion of the lower reflector weighed 43.11 kg.

b. Reactivity Data Pertaining to a Core with 4.90-cm(1.93-in.)-long Cylindrical Mo Reflector Components at Both Ends

At the conclusion of the above experiment, the fuel elements were reconfigured in such a way that one 4.90-cm(1.93-in.)-long cylindrical Mo reflector component was placed adjacent to the active core on one end of the element and two 2.45-cm(0.96-in.)-long cylindrical Mo reflector components were placed end-to-end adjacent to the active core on the other end of the element. These reflector segments were maintained in a position adjacent to the core by means of an aluminum (6061-T6) spacer tube 1.27 cm (0.50 in.) in outside diameter, 1.16 cm (0.46 in.) in inside diameter, and 5.10 cm (2.01 in.) long. Two spacers, one at each end of the fuel element, were placed inside each fuel tube between the end-cap and the Mo segment. On the basis of a sampling of 40 spacers, the average weight of one spacer was determined to be 2.942 gm. The average weight of each Mo segment that was 4.90 cm (1.93 in.) long was 87.20 gm as determined by a sampling of 21 pieces and the average weight of each Mo segment that was 2.45 cm (0.96 in.) long, as determined by an identical sampling, was 43.54 gm. The measured weights of 247 segments each 4.90 cm (1.93 in.) long and 494 segments each 2.45 cm (0.96 in.) long were 21.55530 and 21.55180 kg, respectively. Except for these changes in the cylindrical component of the axial reflector, all other core components, including the 10-cm(3.94-in.)-long eccentric annular axial reflectors, remained unchanged relative to Cores 2.0 and 3.0.

With the cylindrical portion of the axial reflector reduced to approximately one-half its original value (thus reducing the total axial reflector mass to 72.45% of its previous value), a measurement of the all-drums-in excess reactivity was conducted on the core (Core 3.1). This measurement yielded a value (11.7¢) that differed from that for Core 2.0 (168.5¢) by 156.8¢. Thus a loss in reactivity of this amount occurred. Relative to Core 3.0 the loss was 148.4¢.

Since the all-drums-in excess reactivity value for Core 3.1 was down to only 25.7¢ (neglecting the polyethylene boxes) and since the reduction of the cylindrical Mo reflector segments by another factor of 2 would be expected to render the reactor subcritical, a fuel adjustment was carried out. This adjustment consisted of the removal of the 6-rod, 7-wire cluster in each fuel element and its replacement by a 7-rod cluster with no uranium wires. The total mass of uranium in the reassembled core (Core 3.2) was increased uniformly (±1.2 gm in absolute spread) by 2.3246 to 177.2079 kg. The all-drums-in excess reactivity increased by 139.5¢ to 151.2¢. This change in reactivity implies a conversion factor which is significantly greater than that assumed for Cores 2.0 and 3.0 on the basis of prior experiments. The value of 60.0¢/kg was used to derive a critical mass value of 174.69 for Core 3.2. This increase in the conversion factor is possibly the result of increased axial leakage from the core.

A drum calibration was also conducted in Core 3.2 and the data were presented in Figure 13 of Section II-A of this report.

c.  Reactivity Data Pertaining to a Core with 2.45-cm(0.96-in.)-long Cylindrical Mo Reflectors at Both Ends

In order to determine the reactivity effects of reducing the cylindrical Mo reflector segments to approximately one-fourth of their original value, the fuel elements were removed from the core and one of the two 2.45-cm(0.96-in.)-long cylindrical Mo reflectors that were located at the bottom of the element was used to replace the 4.90-cm(1.93-in.)-long reflector segment at the top. Thus each of the 247 fuel elements was changed such that one cylindrical Mo reflector 2.45 cm (0.96 in.) long was located at each end. As was done previously, an aluminum spacer was installed between the lower aluminum endcap and the Mo segment in order to keep the segments adjacent to the active core. These aluminum spacers were 1.27 cm (0.50 in.) in outside diameter, 1.16 cm (0.46 in.) in inside diameter, and 7.55 cm (2.97 in.) long. A sampling of 20 pieces indicated that the average weight of aluminum (6061-T6) per spacer was 4.343 gm. Except for these changes in the cylindrical portion of the axial reflector, all other core components remained unchanged relative to Core 3.2.

Upon reassembling the core (Core 3.3), a measurement of the all-drums-in excess reactivity was conducted. The shorter axial reflectors reduced the excess

from 151.2 to 19.8¢, thus indicating a reactivity change of 131.4¢ as a result of replacing the 4.90-cm(1.93-in.)-long reflector segments by 2.45-cm(0.96-in.)-long reflector segments. Assuming a linear relationship, one would therefore deduce that the reduction of the length of the 494 cylindrical axial reflector segments (247 on each end) from 10 cm (3.94 in.) to 2.45 cm (0.96 in.) would result in a total loss of reactivity of 288.4¢. Also, on the assumption that the core-averaged worth of uranium remained at the previously measured value of 60.0¢/kg, a critical mass value of 176.88 kg of fuel was derived. A measurement, by the continuous drive technique, of the worth of Drums No. 3 and 6 from full-in to full-out was determined in Core 3.3 and was shown in Figure 14 in Section II-A. A step-wise calibration over the short interval from zero degrees of arc to about 50 degrees of arc was also conducted for both Drums No. 3 and 6. The latter results are in reasonably good agreement with the continuous drive information. A total control swing of about 221¢ was observed.

d. Power Distribution Measurements

Two power distribution measurements in this third series of cores were carried out. In the first (Core 3.2), in which the cylindrical axial reflectors were 4.90 cm (1.93 in.) long, one 0.060-cm(0.026-in.)-diam U wire was placed in each of the 27 fuel elements making up the one-twelfth core sector shown in Figure 38. The two drums closest to this one-twelfth sector and the two drums diametrically opposite these were placed in the fuel full-in position and Drums 3 and 6 were banked to 27°20' and 27°15', respectively. After an irradiation of about 1 hour at 38 watts, the wires in Positions 0-1, 10-2, 11-11, 5-3, 4-5, and 8-3 were cut over their entire lengths into approximately 1.27-cm(0.5-in.)-long segments. All of these segments were counted in a NaI crystal spectrometer and the resulting data were corrected for radioactive decay, mass differences, and background count. One 1.27-cm(0.50-in.)-wire segment from the top and one from the midpoint of each of the remaining 21 wires were counted and a similar analysis conducted. The resulting relative power distributions as a function of both radial and axial location were shown in Figures 20 and 21. A tabulation of the results is given in Tables 9 and 10.

Identical power distribution measurements for Core 3.3 [in which the cylindrical axial reflectors were 2.45 cm (0.96 in.) long] were carried out. In this
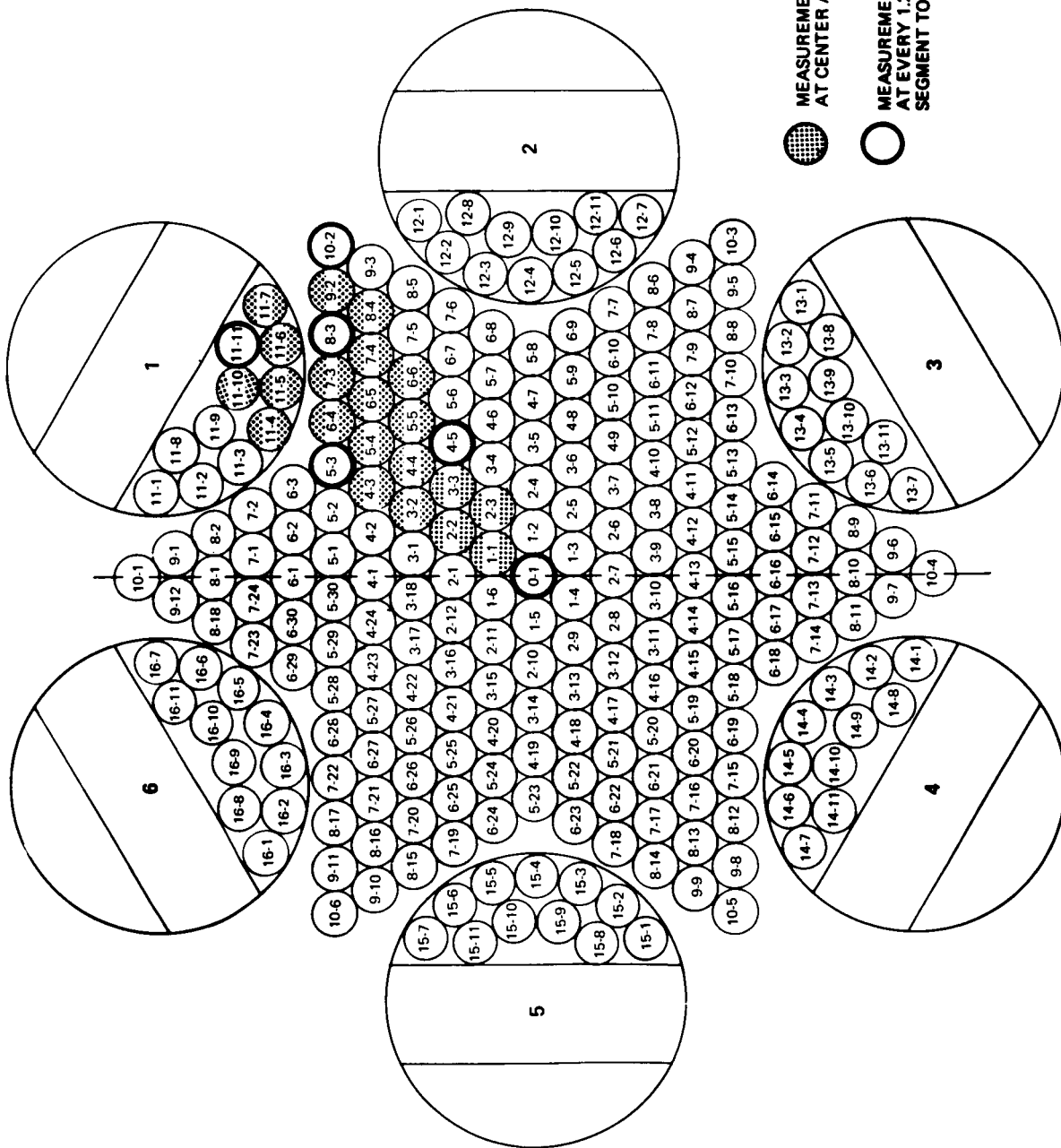
Figure 38. Power Distribution Wire Loading Scheme Shortened Axial Reflectors

7765-4676C

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## TABLE 9

### RADIAL POWER DISTRIBUTION
### (4.94-cm Axial Mo Reflector)

#### RELATIVE POWER

| Wire Segment Number | Radius (cm) | Fuel Element Number | Center (z = 0.0 cm) | Top (z = 17.5 cm) |
|---|---|---|---|---|
| 1 | 0 | 0-1 | 0.994 | 0.657 |
| 2 | 2.18 | 1-1 | 1.003 | 0.652 |
| 3 | 3.85 | 2-3 | 1.036 | 0.674 |
| 4 | 4.40 | 2-2 | 0.974 | 0.680 |
| 5 | 5.87 | 3-3 | 0.986 | 0.675 |
| 6 | 6.67 | 3-2 | 0.958 | 0.639 |
| 7 | 7.70 | 4-5 | 0.954 | 0.631 |
| 8 | 7.98 | 4-4 | 0.976 | 0.655 |
| 9 | 8.85 | 4-3 | 0.931 | 0.646 |
| 10 | 9.64 | 5-5 | 0.914 | 0.603 |
| 11 | 10.16 | 5-4 | 0.876 | 0.601 |
| 12 | 11.07 | 5-3 | 0.838 | 0.547 |
| 13 | 11.47 | 6-6 | 0.851 | 0.572 |
| 14 | 11.75 | 6-5 | 0.831 | 0.551 |
| 15 | 12.30 | 6-4 | 0.887 | 0.602 |
| 16 | 13.45 | 7-4 | 0.803 | 0.534 |
| 17 | 13.77 | 7-3 | 0.788 | 0.522 |
| 18 | 14.68 | 11-4 | 0.763 | 0.507 |
| 19 | 15.20 | 11-5 | 0.743 | 0.495 |
| 20 | 15.28 | 8-4 | 0.753 | 0.500 |
| 21 | 15.48 | 8-3 | 0.736 | 0.502 |
| 22 | 16.59 | 11-6 | 0.696 | 0.456 |
| 23 | 16.89 | 11-10 | 0.708 | 0.477 |
| 24 | 17.26 | 9-2 | 0.702 | 0.471 |
| 25 | 18.34 | 11-11 | 0.658 | 0.418 |
| 26 | 18.53 | 11-7 | 0.623 | 0.400 |
| 27 | 19.13 | 10-2 | 0.641 | 0.418 |

## TABLE 10
## AXIAL POWER DISTRIBUTION
### (4.94-cm Axial Mo Reflector)
## RELATIVE POWER

| Wire Segment Number | Distance From Core Center (cm) | 0-1 (R = 0.0 cm) | 4-5 (R = 7.70 cm) | 5-3 (R = 11.07 cm) | 8-3 (R = 15.48 cm) | 11-11 (R = 18.34 cm) | 10-2 (R = 19.13 cm) |
|---|---|---|---|---|---|---|---|
| Top | | | | | | | |
| 1 | 17.5 | 0.657 | 0.631 | 0.547 | 0.502 | 0.418 | 0.418 |
| 2 | 16.25 | 0.697 | 0.676 | 0.591 | 0.535 | 0.457 | 0.444 |
| 3 | 15.0 | 0.733 | 0.713 | 0.627 | 0.568 | 0.486 | 0.475 |
| 4 | 13.75 | 7.67 | 0.744 | 0.649 | 0.593 | 0.503 | 0.504 |
| 5 | 12.5 | 8.05 | 0.784 | 0.684 | 0.630 | 0.528 | 0.532 |
| 6 | 11.25 | 0.840 | 0.816 | 0.720 | 0.645 | 0.558 | 0.548 |
| 7 | 10.0 | 0.869 | 0.869 | 0.744 | 0.668 | 0.563 | 0.562 |
| 8 | 8.75 | 0.886 | 0.872 | 0.761 | 0.694 | 0.584 | 0.580 |
| 9 | 7.5 | 0.922 | 0.902 | 0.779 | 0.719 | 0.603 | 0.604 |
| 10 | 6.25 | 0.940 | 0.917 | 0.786 | 0.731 | 0.623 | 0.616 |
| 11 | 5.0 | 0.952 | 0.924 | 0.814 | 0.730 | 0.642 | 0.651 |
| 12 | 3.75 | 0.969 | 0.942 | 0.816 | 0.742 | 0.647 | 0.647 |
| 13 | 2.5 | 0.965 | 0.923 | 0.808 | 0.752 | 0.643 | 0.643 |
| 14 | 1.25 | 0.988 | 0.965 | 0.843 | 0.732 | 0.651 | 0.638 |
| 15 | 0.0 | 0.994 | 0.954 | 0.838 | 0.736 | 0.658 | 0.641 |
| 16 | -1.25 | 0.989 | 0.953 | 0.836 | 0.733 | 0.651 | 0.644 |
| 17 | -2.5 | 0.986 | 0.957 | 0.846 | 0.746 | 0.659 | 0.657 |
| 18 | -3.75 | 0.981 | 0.975 | 0.832 | 0.743 | 0.639 | 0.638 |
| 19 | -5.0 | 0.970 | 0.930 | 0.818 | 0.737 | 0.640 | 0.634 |
| 20 | -6.25 | 0.954 | 0.946 | 0.837 | 0.721 | 0.640 | 0.640 |
| 21 | -7.5 | 0.935 | 0.913 | 0.801 | 0.718 | 0.610 | 0.605 |
| 22 | -8.75 | 0.901 | 0.882 | 0.766 | 0.718 | 0.619 | 0.592 |
| 23 | -10.0 | 0.896 | 0.871 | 0.762 | 0.680 | 0.597 | 0.587 |
| 24 | -11.25 | 0.883 | 0.845 | 0.737 | 0.661 | 0.581 | 0.567 |
| 25 | -12.5 | 0.834 | 0.810 | 0.708 | 0.645 | 0.562 | 0.544 |
| 26 | -13.75 | 0.820 | 0.791 | 0.684 | 0.615 | 0.541 | 0.524 |
| 27 | -15.0 | 0.780 | 0.754 | 0.659 | 0.579 | 0.516 | 0.500 |
| 28 | -16.25 | 0.743 | 0.717 | 0.632 | 0.562 | 0.487 | 0.473 |
| 29 | -17.5 | 0.706 | 0.686 | 0.598 | 0.531 | 0.464 | 0.454 |
| Bottom | | | | | | | |

case, Drums 3 and 6 were banked to 31°0' to maintain level power and all other drums were placed with fuel full-in. For irradiation purposes, the locations of the uranium wires corresponded to those shown in Figure 38. The wire segments were cut and counted, and the data were analyzed as outlined above. The results were previously shown in Figures 22 and 23, and are tabulated in Tables 11 and 12.

## 5. Reactivity Worth of a Uniform Addition of Tungsten (Cores 4.0 through 4.3)

In Core 3.3, the fuel configuration in each of the 247 fuel elements consisted of a 7-rod cluster of 0.432-cm(0.170-in.)-diam U rods with no large diameter 0.152-cm(0.060-in.) U wires. The cylindrical axial Mo reflectors were 2.45 cm (0.96 in.) high on both the top and bottom of each fuel element. In order to measure the reactivity worth of uniform additions of W, the fuel elements were unloaded and were re-configured to achieve a 6-rod cluster with 6 of the 0.152-cm(0.060-in.)-diam uranium wires. The upper and lower cylindrical Mo reflectors were changed to 10.00 cm (3.94 in.) and 9.84 cm (3.88 in.), respectively. The total mass of uranium in the core, distributed uniformly within ±1.2 gm, was 171.86181 kg. The all-drums-in excess reactivity of this core (Core 4.0) was determined to be 23.5¢ without correction for the polyethylene boxes, and 9.5¢ after correction for the polyethylene boxes. As can be seen in Table 2, if a conversion factor of 50.6¢/kg is assumed (on the basis of measurements performed on the previous program), a critical mass of 171.67 kg is derived for this base case. This value of the critical mass is in very good agreement with that obtained for Core 3.0 (see Table 2) to which it is identical in terms of non-fuel materials. It differs only slightly from that for Core 2.0 which has full-length axial reflectors on both top and bottom. The difference is in the direction that would be expected as a result of the slightly shorter axial reflectors on one end of the elements of Core 4.0. From the data for Cores 3.0 and 4.0, a core-average worth for fuel is calculated to be 49.8¢/kg. On the basis of this value for the conversion factor, a critical mass identical, within statistical uncertainties to that quoted above, is obtained.

After obtaining the all-drums-in excess reactivity for Core 4.0, a W rod, 0.457 cm (0.18 in.) in diameter by 37.53 cm (14.77 in.) long, was added to the center of each fuel cluster in each of the 247 fuel elements. The all-drums-in

## TABLE 11

### RADIAL POWER DISTRIBUTION
### (2.45-cm Axial Mo Reflector)

### RELATIVE POWER

| Wire Segment Number | Radius (cm) | Fuel Element Number | Center (z = 0.0 cm) | Top (z = 17.5 cm) |
|---|---|---|---|---|
| 1 | 0 | 0-1 | 0.987 | 0.616 |
| 2 | 2.18 | 1-1 | 0.993 | 0.648 |
| 3 | 3.85 | 2-3 | 0.965 | 0.656 |
| 4 | 4.40 | 2-2 | 0.966 | 0.635 |
| 5 | 5.87 | 3-3 | 0.964 | 0.614 |
| 6 | 6.67 | 3-2 | 0.925 | 0.631 |
| 7 | 7.70 | 4-5 | 0.931 | 0.629 |
| 8 | 7.98 | 4-4 | 0.927 | 0.618 |
| 9 | 8.85 | 4-3 | 0.886 | 0.563 |
| 10 | 9.64 | 5-5 | 0.922 | 0.578 |
| 11 | 10.16 | 5-4 | 0.872 | 0.561 |
| 12 | 11.07 | 5-3 | 0.846 | 0.561 |
| 13 | 11.47 | 6-6 | 0.857 | 0.566 |
| 14 | 11.75 | 6-5 | 0.826 | 0.539 |
| 15 | 12.30 | 6-5 | 0.789 | 0.519 |
| 16 | 13.45 | 7-4 | 0.806 | 0.531 |
| 17 | 13.77 | 7-3 | 0.771 | 0.495 |
| 18 | 14.68 | 11-4 | 0.763 | 0.488 |
| 19 | 15.20 | 11-5 | 0.733 | 0.468 |
| 20 | 15.28 | 8-4 | 0.755 | 0.489 |
| 21 | 15.48 | 8-3 | 0.730 | 0.498 |
| 22 | 16.59 | 11-6 | 0.712 | 0.455 |
| 23 | 16.89 | 11-10 | 0.678 | 0.466 |
| 24 | 17.26 | 9-2 | 0.703 | 0.431 |
| 25 | 18.34 | 11-11 | 0.645 | 0.409 |
| 26 | 18.53 | 11-7 | 0.630 | 0.388 |
| 27 | 19.13 | 10-2 | 0.609 | 0.404 |

## TABLE 12

### AXIAL POWER DISTRIBUTION
(2.45-cm Axial Mo Reflector)

### RELATIVE POWER

| Wire Segment Number | Distance From Core Center (cm) | 0-1 (R = 0.0 cm) | 4-5 (R = 7.70 cm) | 5-3 (R = 11.07 cm) | 8-3 (R = 15.48 cm) | 11-11 (R = 18.34 cm) | 10-2 (R = 19.13 cm) |
|---|---|---|---|---|---|---|---|
| Top | | | | | | | |
| 1 | 17.5 | 0.616 | 0.629 | 0.561 | 0.498 | 0.409 | 0.404 |
| 2 | 16.25 | 0.677 | 0.667 | 0.588 | 0.525 | 0.444 | 0.431 |
| 3 | 15.0 | 0.713 | 0.707 | 0.621 | 0.564 | 0.477 | 0.455 |
| 4 | 13.75 | 0.755 | 0.753 | 0.622 | 0.585 | 0.503 | 0.476 |
| 5 | 12.5 | 0.789 | 0.780 | 0.693 | 0.614 | 0.627 | 0.491 |
| 6 | 11.25 | 0.822 | 0.806 | 0.724 | 0.634 | 0.547 | 0.516 |
| 7 | 10.0 | 0.842 | 0.826 | 0.744 | 0.649 | 0.573 | 0.542 |
| 8 | 8.75 | 0.868 | 0.871 | 0.775 | 0.660 | 0.584 | 0.568 |
| 9 | 7.5 | 0.896 | 0.880 | 0.772 | 0.676 | 0.605 | 0.576 |
| 10 | 6.26 | 0.931 | 0.904 | 0.786 | 0.687 | 0.651 | 0.581 |
| 11 | 5.0 | 0.941 | 0.916 | 0.818 | 0.702 | 0.641 | 0.600 |
| 12 | 3.75 | 0.964 | 0.923 | 0.815 | 0.715 | 0.635 | 0.601 |
| 13 | 2.5 | 0.981 | 0.931 | 0.821 | 0.715 | 0.650 | 0.604 |
| 14 | 1.25 | 0.977 | 0.944 | 0.820 | 0.720 | 0.649 | 0.612 |
| 15 | 0.0 | 0.987 | 0.931 | 0.846 | 0.730 | 0.645 | 0.609 |
| 16 | -1.25 | 0.985 | 0.948 | 0.851 | 0.732 | 0.650 | 0.608 |
| 17 | -2.5 | 0.995 | 0.929 | 0.838 | 0.726 | 0.649 | 0.614 |
| 18 | -3.75 | 0.987 | 0.941 | 0.832 | 0.715 | 0.643 | 0.606 |
| 19 | -5.0 | 0.976 | 0.929 | 0.779 | 0.717 | 0.627 | 0.597 |
| 20 | -6.26 | 0.962 | 0.916 | 0.815 | 0.720 | 0.622 | 0.598 |
| 21 | -7.5 | 0.958 | 0.883 | 0.821 | 0.692 | 0.609 | 0.576 |
| 22 | -8.75 | 0.933 | 0.880 | 0.785 | 0.676 | 0.595 | 0.564 |
| 23 | -10.0 | 0.918 | 0.841 | 0.763 | 0.669 | 0.569 | 0.542 |
| 24 | -11.25 | 0.883 | 0.827 | 0.744 | 0.649 | 0.567 | 0.535 |
| 25 | -12.5 | 0.841 | 0.800 | 0.730 | 0.629 | 0.536 | 0.522 |
| 26 | -13.75 | 0.817 | 0.770 | 0.700 | 0.606 | 0.519 | 0.500 |
| 27 | -15.0 | 0.791 | 0.720 | 0.667 | 0.578 | 0.492 | 0.468 |
| 28 | -16.26 | 0.752 | 0.693 | 0.643 | 0.539 | 0.466 | 0.454 |
| 29 | -17.5 | 0.719 | 0.668 | 0.608 | 0.523 | 0.436 | 0.426 |
| Bottom | | | | | | | |

excess reactivity for this core (designated Core 4.1 — see Table 2) was measured to be 81.1¢ after correction for the polyethylene boxes. The change in the excess was therefore 71.6¢ and, since a total of 29.40864 kg of W were added, the worth per unit mass of W was derived to be +2.43 ¢/kg.

A total of 15.13 kg of W foil was next added to the core in a uniform manner to bring the total content of W to 44.54 kg, 61.3 gm being added on the average to each fuel element. The all-drums-in excess reactivity was again determined for the core (Core 4.2) and found to be 131.9¢ after correction for the polyethylene boxes. The change in reactivity relative to Core 4.0 was therefore 122.4¢, a value that results in a core-average worth for W of +2.75 ¢/kg. However, the core averaged worth of W is +3.36 ¢/kg on the basis of the 15.13 kg addition alone.

In order to obtain an independent determination of the conversion factor, or core-averaged worth of uranium fuel, as it would apply to the core fully loaded with W, one U wire was removed from every other fuel element and a new all-drums-in excess reactivity was established. The total mass of uranium wire removed was 1.60670 kg and the change in reactivity was 90.3¢; consequently, a conversion factor of 56.2 ¢/kg was obtained. Using the latter value, one obtains a value of 169.51 kg for the critical mass of Core 4.2.

Drum calibration curves were generated during the course of the work concerning the W additions. A typical result was shown in Figure 15. The total control swing of the drum from full-in to full-out was about 222.0¢.

6. Physics Characteristics of a $B_4C$-Controlled Reactor (Cores 5.0 and 5.1)

a. Core Description

A series of investigations was initiated, upon completion of the studies of the reactivity effects of tungsten, to determine the critical mass, control characteristics, and relative power distribution in a $B_4C$-controlled reactor. In order to accomplish this objective, each of the six standard control drums was removed from the critical assembly and modified in the following way: (1) the eleven fuel elements were removed and replaced by an aluminum canister whose cross sectional area in the horizontal plane corresponded to the circular segment of the drum cross section occupied by fuel elements, and (2) the Ta absorber

segment was removed and replaced by another smaller aluminum canister whose outside dimensions were very nearly identical to the absorber segment it replaced. A photograph of these two canisters is shown in Figure 5.

Each of the six larger canisters was filled with $B_4C$ powder. Initially 44 kg of natural $B_4C$ powder was procured. Of the 44 kg, about 28 kg consisted of particles in the size range of -6 to +12 U.S. Standard Sieve Size, about 6 kg consisted of particles in the size range of -35 to +100 U.S. Standard Sieve Size, and the remainder consisted of particles in the size range -200 U.S. Standard Sieve Size. The three size distributions were blended together in such a way that 67.5 wt % of the final mix consisted of the larger particles, 12.5 wt % consisted of the medium size particles, and the balance was made up of the fine particles. The blended mixture of $B_4C$ particles was then poured into the aluminum canisters while the latter were vibrated on a standard laboratory vibrator. The final specifications for the finished canisters are given in Table 13.

TABLE 13

WEIGHTS OF $B_4C$-FILLED CANISTERS AND CONTENTS

| Canister Number | Weight of Canister (gm) | Weight of B4C (gm) | Percent[*] of T.D. |
|---|---|---|---|
| 1 | 1058.2 | 5,492.2 | 69.4 |
| 2 | 1055.2 | 5,376.8 | 67.9 |
| 3 | 1053.3 | 5.382.6 | 68.0 |
| 4 | 1055.5 | 5,366.5 | 67.8 |
| 5 | 1055.0 | 5,291.3 | 66.8 |
| 6 | 1056.1 | 5,297.8 | 66.9 |
| Total | 6333.3 | 32,307.2 | |

[*]The volume of one canister was measured to be 3,142 cm$^3$.
The mass of B4C which would occupy this volume at 100% theoretical density (T.D.) is 7,917.8 gm.

Upon completion of the loading of the $B_4C$ powder into the six aluminum canisters, the canisters were mounted, by means of two alignment pins that fitted into the drum grid plate, on the control drums in the place normally occupied by the eleven fuel elements.
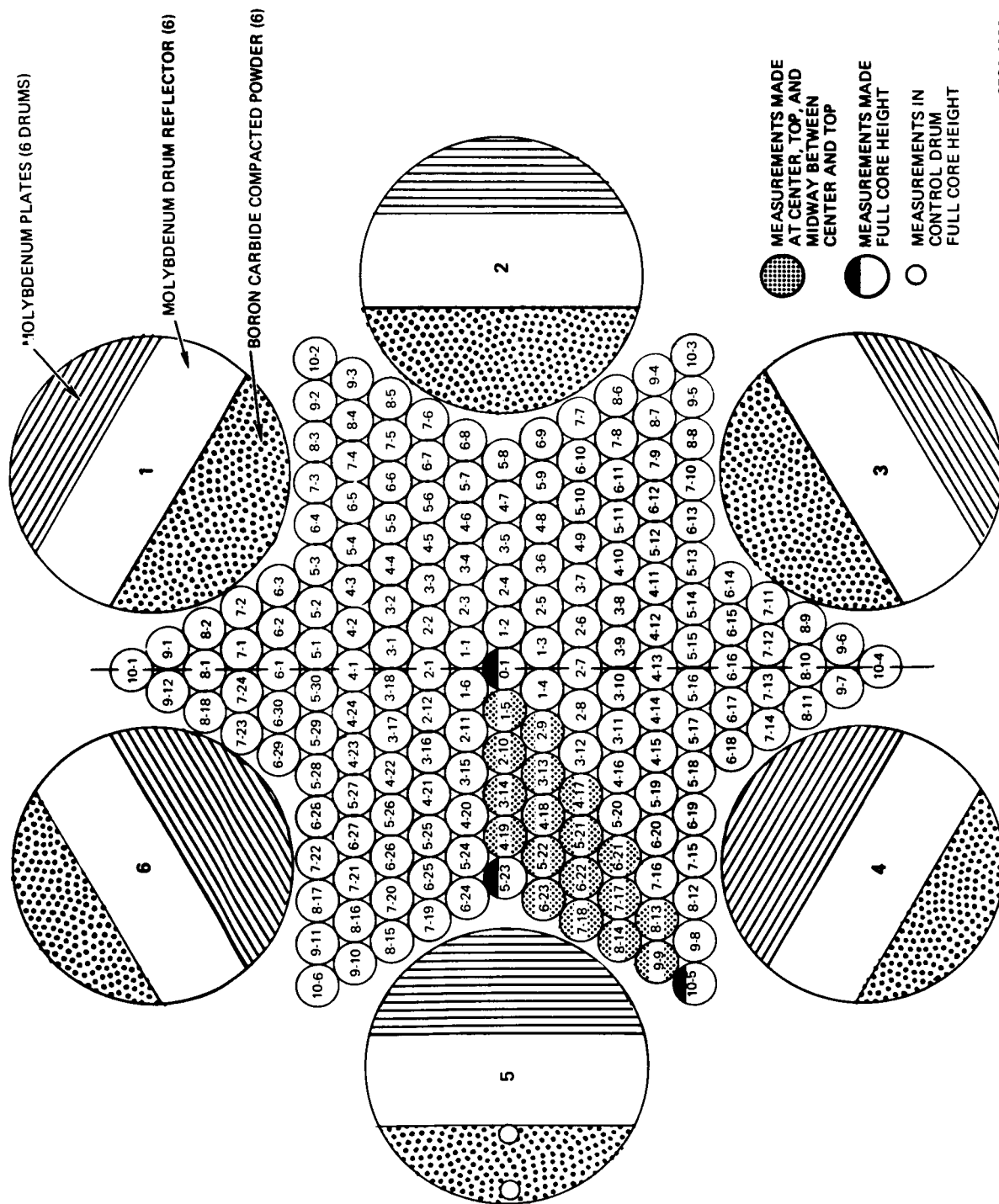
Figure 39. Power Distribution Wire Loading Scheme
B₄C-Controlled Reactor

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Each of the six smaller canisters was filled with eleven plates of Mo metal (see Figure 5) each 58.7 cm (23.1 in.) long by 0.318 cm (0.125 in.) thick by various widths. These plates were stacked in stair-step fashion so as to occupy as much of the available volume as possible without resorting to curved edges. The plates had widths of 2.10 cm (0.827 in.), 4.73 cm (1.864 in.), 6.29 cm (2.476 in.), 7.47 cm (2.941 in.), 8.44 cm (3.322 in.), 9.26 cm (3.64 in.), 9.97 cm (3.925 in.) 10.59 cm (4.169 in.), 11.14 cm (4.385 in.), 11.62 cm (4.576 in.), and 12.05 cm (4.745 in.). Once the eleven Mo plates were installed, an aluminum plate, 0.79 cm (0.312 in.) thick, was placed on each end of the canister and the canister was attached to the grid plate of the drum in the same manner as the Ta absorber segment. The final specifications for the Mo-plate-filled canister are given in Table 14. A core layout diagram for the $B_4C$-controlled system is shown in Figure 39 which also gives data pertaining to a power distribution measurement to be discussed below.

TABLE 14

WEIGHTS OF Mo-FILLED CANISTERS AND CONTENTS

| Canister Number | Weight of Canister (gm) | Weight of Mo (gm) |
|---|---|---|
| 1 | 841.55 | 17,938.65 |
| 2 | 845.58 | 18,068.32 |
| 3 | 848.25 | 17,951.75 |
| 4 | 849.35 | 17,998.55 |
| 5 | 840.40 | 18,014.60 |
| 6 | 848.75 | 17,986.55 |
| Totals | 5,073.88 | 107.95842 kg |

On the basis of an anticipated critical mass of 142 kg (as provided by NASA), the 181 fuel elements in the stationary part of the core were removed, the fuel cluster was unloaded, and a new cluster consisting of 7 rods [each 0.432 cm (0.170 in.) in diameter] and 6 wires [each 0.152 cm (0.060 in.) in diameter] was installed. No other materials were placed within the fuel tube; consequently the individual element loading for non-fuel materials was identical to that of Cores 2.0, 3.0, and 4.0. However, since there were only 181 fuel elements,
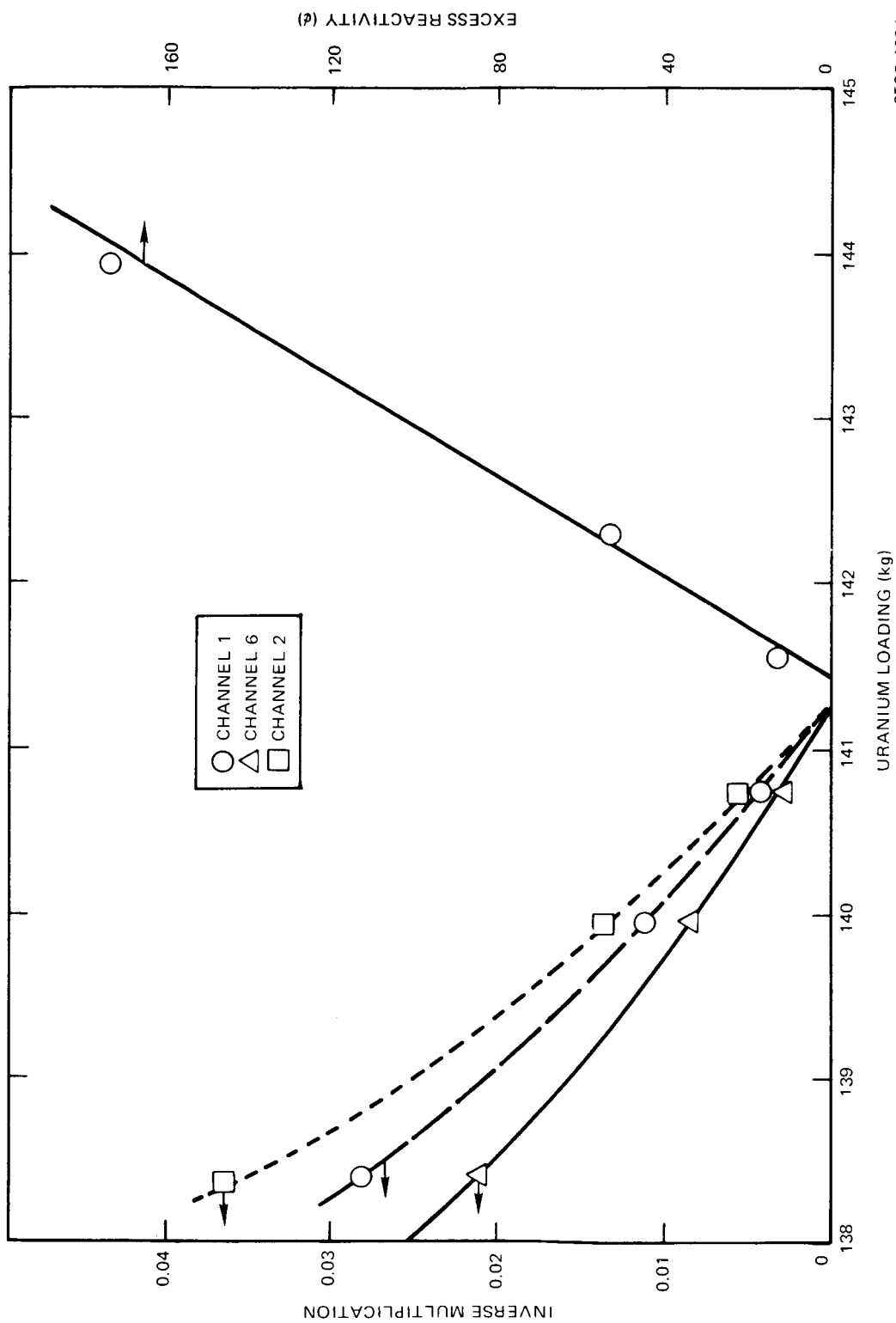
Figure 40. Excess Reactivity and Inverse Multiplication Values for the $B_4C$-Controlled Reactor

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the total quantities of Ta, $Li_3{}^7N$, and Mo reflector materials in the core were reduced by the ratio of 181 to 247. These new mass values were listed previously in Table 2, along with the changes in the materials making up the drums.

b.  Critical Mass

Upon completion of the loading of the fuel clusters into the fuel elements, an inverse-multiplication approach to critical was initiated. Criticality was achieved when 178 elements were in place. A plot of inverse multiplication as a function of uranium loading (Figure 40), extrapolated to a value of about 141.2 kg for K = 1.0. Upon the addition of the three remaining fuel elements (9-4, 9-12, and 0-1), an all-drums-in excess reactivity (Mo full-in) of 174.6¢ was achieved. The core excess reactivity values corresponding to the addition of the 178th fuel element, 9-4, and, finally, 9-12 and 0-1 simultaneously do not lie on a straight line since they do not represent additions of fuel in approximately core average worth locations. They nevertheless tend to substantiate a critical mass value of about 141.2 kg. The total uranium mass in the core (Core 5.0) with all 181 fuel elements in place, was 143.92945 kg as indicated in Table 2.

After the completion of the above task, one uranium wire was removed from every even-numbered fuel element in order to determine the core-averaged worth of uranium. In this process, 1.19166 kg of uranium were removed, whereupon the excess reactivity was measured to be about 98.0¢. This change in reactivity resulted in a core-averaged worth for fuel of 64.2¢/kg. The critical mass was therefore derived to be 141.43 kg after correction for the polyethylene boxes that surround the neutron detectors.

c.  Control Drum Worths

With the reactor fully loaded with 143.92945 kg of uranium, a series of drum calibrations by the step-wise and continuous drive techniques was performed. The worth of each of the six drums, driven individually, was measured from full-in to full-out. A typical plot, one applying to a step-wise calibration of Drum No. 3, was given in Figure 16. In the $B_4C$-controlled reactor, zero degrees of arc refers to the Mo-filled canister placed in the full-in position. This orientation places the $B_4C$ canister in the full-out position. The worth of Drum No. 3 is seen in the figure to be about 193.2¢. The reactivity

worths of the remaining 5 drums are essentially identical, the average being about 194¢ and the absolute spread being ±3¢ about that average.

A check on the control swing afforded by a single drum was obtained by means of a series of period measurements. In order to accomplish this task, Drum 6 was placed with the $B_4C$ sector full-in (180°) and Drum 3 was banked to maintain a just critical reactor (21°0'). Drum 6 was then turned in a few degrees and held there while a stable period was achieved. The position of Drum 6 was noted and the period was measured. Drum 3 was then banked out to reduce the excess reactivity to zero and to achieve level power. A new period measurement would then be made by turning Drum 6 in a few more degrees. The results of this series of measurements is given in Table 15, where the total worth of Drum 6 is shown to be 191.8¢, a value in good agreement with the results discussed above.

The reactivity worth of all drums ganged was measured from 40 to 180° ($B_4C$ full-in) by means of the source multiplication (or inverse counting) technique. In order to conduct this experiment, the fuel element in Position 0-1 was

TABLE 15

REACTIVITY WORTH OF DRUM NO. 6 BY PERIOD MEASUREMENTS

| Run Number | Drum No. 3 Position | Drum No. 6* Position (°) | | Period (sec) | Reactivity Change (¢) | Cumulative Reactivity (¢) |
|---|---|---|---|---|---|---|
| | | From | To | | | |
| 1 | 21°0' | 180 | 155 | 40.0 | 18.5 | 18.5 |
| 2 | 46°30' | 155 | 140 | 36.0 | 19.8 | 38.3 |
| 3 | 62°20' | 140 | 128 | 41.5 | 18.1 | 56.4 |
| 4 | 75°40' | 128 | 115 | 31.0 | 21.7 | 78.1 |
| 5 | 89°0' | 115 | 102 | 32.0 | 21.3 | 99.4 |
| 6 | 102°7' | 102 | 90 | 34.5 | 20.3 | 119.7 |
| 7 | 113°5' | 90 | 78 | 35.0 | 20.1 | 139.8 |
| 8 | 125°12' | 78 | 63 | 33.0 | 20.9 | 160.7 |
| 9 | 139°52' | 63 | 45 | 41.5 | 18.1 | 178.8 |
| 10 | 155°42' | 45 | 2 | 67.0 | 13.0 | 191.8 |

*$B_4C$ sector is full-in at 180° position.

removed from the fully-loaded core and a dummy element containing a $Cf^{252}$ source was put in its place. All drums were then banked equally to establish a critical position ($\sim 40°$). Subsequently, all drums were turned simultaneously to 46, 52, 57, 61, 78, 100, 120, 140, 160, and 175°. A source multiplication value was determined at each position. In a separate run, the degree of subcriticality with all drums ganged to 46, 52, 57, and 61° (-30.7, -66.9, -101.4, and -131.0¢) was measured by the inverse kinetics method. On the basis of the measured worth at 46° (the normalization point), the source multiplication data were converted to reactivity as indicated in Figure 41. The worth of all drums from full-in to full-out was therefore derived to be about $11.98, a value in good agreement with the worth of one drum multiplied by 6. The degree of subcriticality predicted on the basis of the source multiplication data is also in good agreement with the inverse kinetics data at 52, 57, and 61°; consequently, the results are independent of the normalization point for the points investigated. The counting data were taken on Channels 1, 2, and 6, and all three yielded nearly identical results.

d. Power Distribution

The power distribution in a one-twelfth sector of the $B_4C$-controlled reactor was determined by irradiating one uranium wire [0.066 cm (0.026 in.) diam] in each of the 23 positions indicated in Figure 39. Five of the wires were segmented over their entire length and all segments were counted to determine the axial power distribution from the top to the bottom of the core. Three segments were cut from each of the remaining 18 wires — one from the midplane, one from the top, and one halfway in between — to establish, along with corresponding segments from the first 5-wire segments, the power distribution in the radial direction. The measured activities were plotted in Figures 24 and 25 and tabulated in Tables 16 and 17. The irradiation was conducted with the reactor operating at a constant power of 38 watts for a period of 1 hour. Drums 4, 5, and 6 were placed in the Mo-full-in position (see Figure 39), while Drums 1, 2, and 3 were all banked equally at 75°40'. Four anomalous activity values in the radial power distribution were observed and are noted in Table 16. These data points, for unexplained reasons, lay well outside of statistical uncertainties.

BORON CARBIDE CONTROLLED REACTOR
UNIFORM FUEL DISTRIBUTION
URANIUM MASS — 143.92945 kg

WORTH OF ALL DRUMS ($)

DRUM POSITION (degrees of arc)
(ZERO DEGREES = MOLYBDENUM FULL IN)
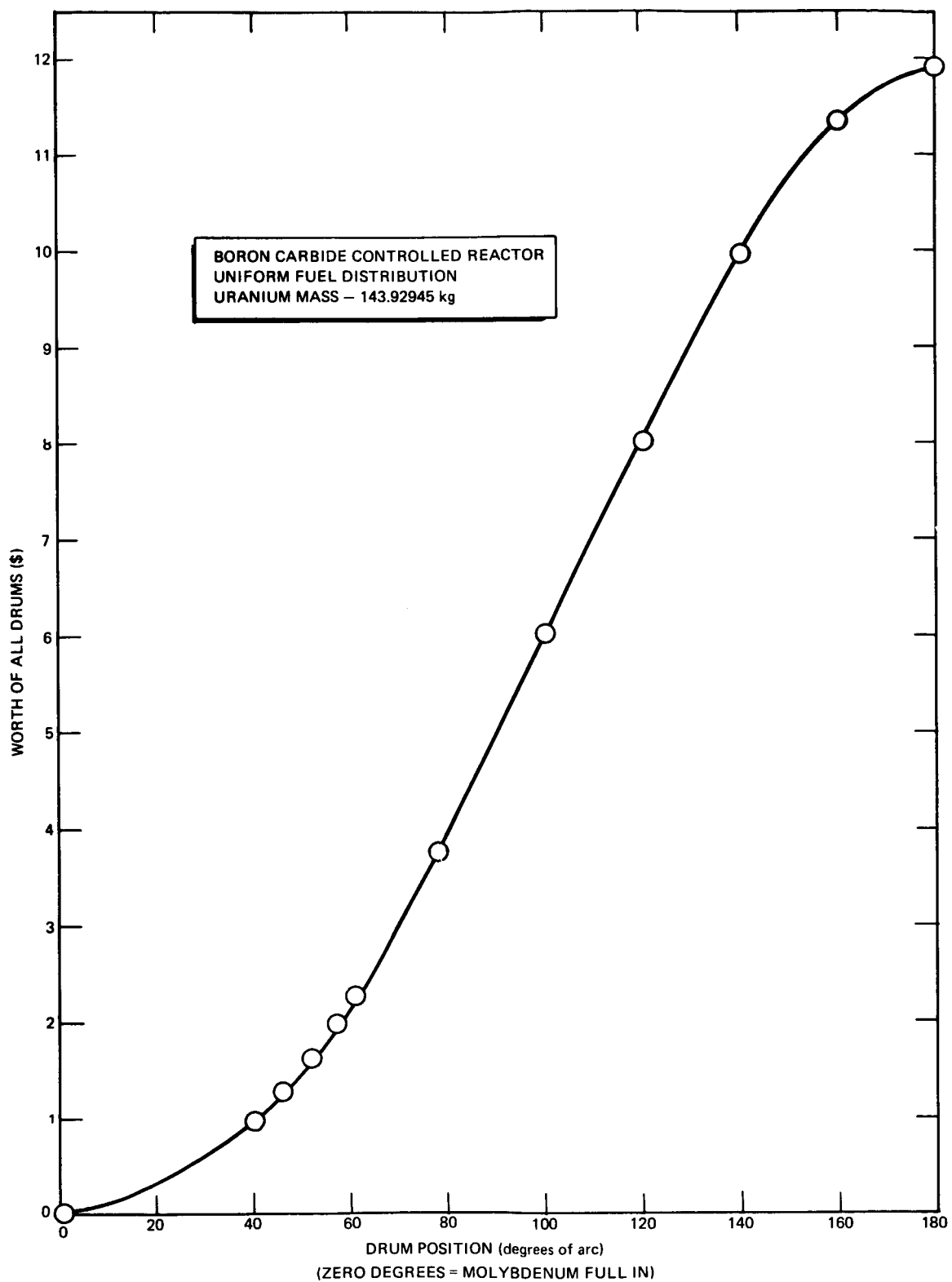
6526-4625

Figure 41.   Worth of All Drums Ganged for Core 5.0
(B$_4$C-Controlled Reactor)

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## TABLE 16

### RELATIVE RADIAL POWER DISTRIBUTION

### $B_4$C-CONTROLLED REACTOR

| Wire Segment Number | Radius (cm) | Fuel Element Number | Center (z = 0.0 cm) | Midway (z = 8.75 cm) | Top (z = 17.5 cm) |
|---|---|---|---|---|---|
| 1 | 0.0 | 0-1 | 0.983 | 0.889 | 0.646 |
| 2 | 2.18 | 1-5 | 0.970 | 0.962* | 0.642 |
| 3 | 3.85 | 2-9 | 0.971 | 0.889 | 0.640 |
| 4 | 4.40 | 2-10 | 0.976 | 0.873 | 0.629 |
| 5 | 5.87 | 3-13 | 0.951 | 0.870 | 0.622 |
| 6 | 6.67 | 3-14 | 0.940 | 0.861 | 0.623 |
| 7 | 7.70 | 4-17 | 0.921 | 0.833 | 0.672* |
| 8 | 7.98 | 4-18 | 0.849* | 0.837 | 0.593 |
| 9 | 8.85 | 4-19 | 0.898 | 0.818 | 0.594 |
| 10 | 9.64 | 5-21 | 0.868 | 0.867 | 0.571 |
| 11 | 10.16 | 5-22 | 0.859 | 0.762 | 0.546 |
| 12 | 11.07 | 5-23 | 0.775* | 0.725 | 0.545 |
| 13 | 11.47 | 6-21 | 0.814 | 0.744 | 0.532 |
| 14 | 11.75 | 6-22 | 0.815 | 0.709 | 0.510 |
| 15 | 12.30 | 6-23 | 0.789 | 0.722 | 0.505 |
| 16 | 13.45 | 7-17 | 0.747 | 0.681 | 0.499 |
| 17 | 13.77 | 7-18 | 0.737 | 0.672 | 0.485 |
| 18 | 15.28 | 8-13 | 0.684 | 0.605 | 0.442 |
| 19 | 15.48 | 8-14 | 0.677 | 0.606 | 0.441 |
| 20 | 17.26 | 9-9 | 0.610 | 0.544 | 0.397 |
| 21 | 19.13 | 10-5 | 0.515 | 0.475 | 0.339 |
| 22 | 22.99 | Drum (Flat) | 0.241 | 0.216 | 0.156 |
| 23 | 27.81 | Drum (Curve) | 0.1084 | 0.0908 | 0.0572 |

*Unexplained anomalies

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# TABLE 17

## RELATIVE AXIAL POWER DISTRIBUTION

## $B_4C$-CONTROLLED REACTOR

| Wire Segment Number | Distance From Core Center (cm) | 0-1 (R = 0.0 cm) | 5-23 (R = 11.07 cm) | 10-5 (R = 19.13 cm) | Drum Flat (R = 22.99 cm) | Drum Curve (R = 27.81 cm) |
|---|---|---|---|---|---|---|
| Top | | | | | | |
| 1 | 17.5 | 0.646 | 0.545 | 0.339 | 0.156 | 0.0572 |
| 2 | 16.25 | 0.697 | 0.583 | 0.364 | 0.168 | 0.0626 |
| 3 | 15.0 | 0.737 | 0.615 | 0.393 | 0.181 | 0.0677 |
| 4 | 13.75 | 0.770 | 0.638 | 0.407 | 0.191 | 0.0740 |
| 5 | 12.5 | 0.797 | 0.671 | 0.425 | 0.196 | 0.0769 |
| 6 | 11.25 | 0.827 | 0.686 | 0.448 | 0.204 | 0.0808 |
| 7 | 10.0 | 0.862 | 0.705 | 0.463 | 0.210 | 0.0877 |
| 8 | 8.75 | 0.889 | 0.725 | 0.475 | 0.216 | 0.0908 |
| 9 | 7.5 | 0.912 | 0.755 | 0.487 | 0.230 | 0.0970 |
| 10 | 6.25 | 0.925 | 0.766 | 0.486 | 0.233 | 0.1007 |
| 11 | 5.0 | 0.944 | 0.760 | 0.496 | 0.233 | 0.1026 |
| 12 | 3.75 | 0.954 | 0.781 | 0.504 | 0.240 | 0.1026 |
| 13 | 2.5 | 0.969 | 0.790 | 0.507 | 0.247 | 0.1064 |
| 14 | 1.25 | 0.982 | 0.788 | 0.507 | 0.236 | 0.1079 |
| 15 | 0.0 | 0.983 | 0.775 | 0.515 | 0.241 | 0.1084 |
| 16 | -1.25 | 0.980 | 0.778 | 0.519 | 0.236 | 0.1086 |
| 17 | -2.5 | 0.984 | 0.770 | 0.510 | 0.238 | 0.1084 |
| 18 | -3.75 | 0.986 | 0.769 | 0.499 | 0.234 | 0.1077 |
| 19 | -5.0 | 0.968 | 0.750 | 0.501 | 0.230 | 0.1074 |
| 20 | -6.25 | 0.952 | 0.764 | 0.491 | 0.228 | 0.1042 |
| 21 | -7.5 | 0.943 | 0.752 | 0.485 | 0.223 | 0.1000 |
| 22 | -8.75 | 0.920 | 0.725 | 0.472 | 0.215 | 0.0994 |
| 23 | -10.0 | 0.901 | 0.708 | 0.454 | 0.206 | 0.0954 |
| 24 | -11.25 | 0.871 | 0.697 | 0.457 | 0.201 | 0.0944 |
| 25 | -12.5 | 0.830 | 0.673 | 0.443 | 0.191 | 0.0926 |
| 26 | -13.75 | 0.811 | 0.643 | 0.416 | 0.183 | 0.0867 |
| 27 | -15.0 | 0.776 | 0.619 | 0.404 | 0.175 | 0.0850 |
| 28 | -16.25 | 0.721 | 0.571 | 0.309 | 0.160 | 0.0807 |
| 29 | -17.5 | 0.691 | 0.547 | 0.350 | 0.150 | 0.0740 |
| Bottom | | | | | | |

7. Reactivity Effects of Adding Polyethylene to a Uniformly Loaded Core (Cores 6.0 through 6.15, Inclusive)

a. The Base-Case Core

The $B_4C$-controlled reactor was completely disassembled, the $B_4C$- and Mo-filled canisters were removed from the drums, the Ta absorber segment was re-installed, and a re-configuration of the fuel cluster and other fuel element materials was initiated in order to reestablish a 247-fuel-element configuration. The fuel cluster for the core designated 6.0 (see Table 2) consisted of 6 uranium rods and 7 uranium wires. Non-fuel materials in each of the 247 uniformly loaded elements consisted of 1 Ta wire 0.279 cm (0.110 in.) in diameter, a coil of Hf foil and a coil of Ta foil. The total Ta content of the active core, including fuel and honeycomb tubes, was 80.25 kg. Other material weights are delineated in Tables 1 and 2. This core configuration, which had a total uranium loading of 174.24874 kg, was essentially identical to a core assembled on the previous program and designated composition 4A (see Reference 1).

Upon re-assembling the reactor, the all-drums-in excess reactivity was measured to be 90.2¢, after correction for the polyethylene boxes. The removal of one uranium wire from every even numbered fuel element (Core 6.1) decreased the total U mass to 172.63355 kg and decreased the all-drums-in excess to 7.5¢. This change in reactivity, in relation to the fuel loading change, results in a core-averaged worth of fuel of 51.2¢/kg. On the basis of the latter conversion factor, a critical mass of 172.49 kg results.

b. Description of Polyethylene Strips and Loading Techniques

The core was next restored to its original condition (i.e., 7 U wires per cluster) and the addition of polyethylene was initiated. Polyethylene was inserted in the form of strips, triangular in cross section, and 37.50 cm (14.75 in.) long. These strips, some of which are shown in Figure 42, were designed to fit into interstitial positions between the fuel elements of the core and to extend only over the active core region [37.58 cm (14.80 in.)]. The specification for the cross sectional dimension was as follows: all sides of the triangle are equal in length and the triangle circumscribes a circle 0.376 cm (0.148 in.) ± 0.007 cm (0.003 in.) in diameter. This diameter represented the largest circle that could be used and still assure that all strips would fit into the core.

POLYETHYLENE STRIPS
WITH ALUMINUM
MOUNTING WIRE
IN PLACE

POLYETHYLENE STRIPS
WITHOUT ALUMINUM
MOUNTING WIRE
IN PLACE

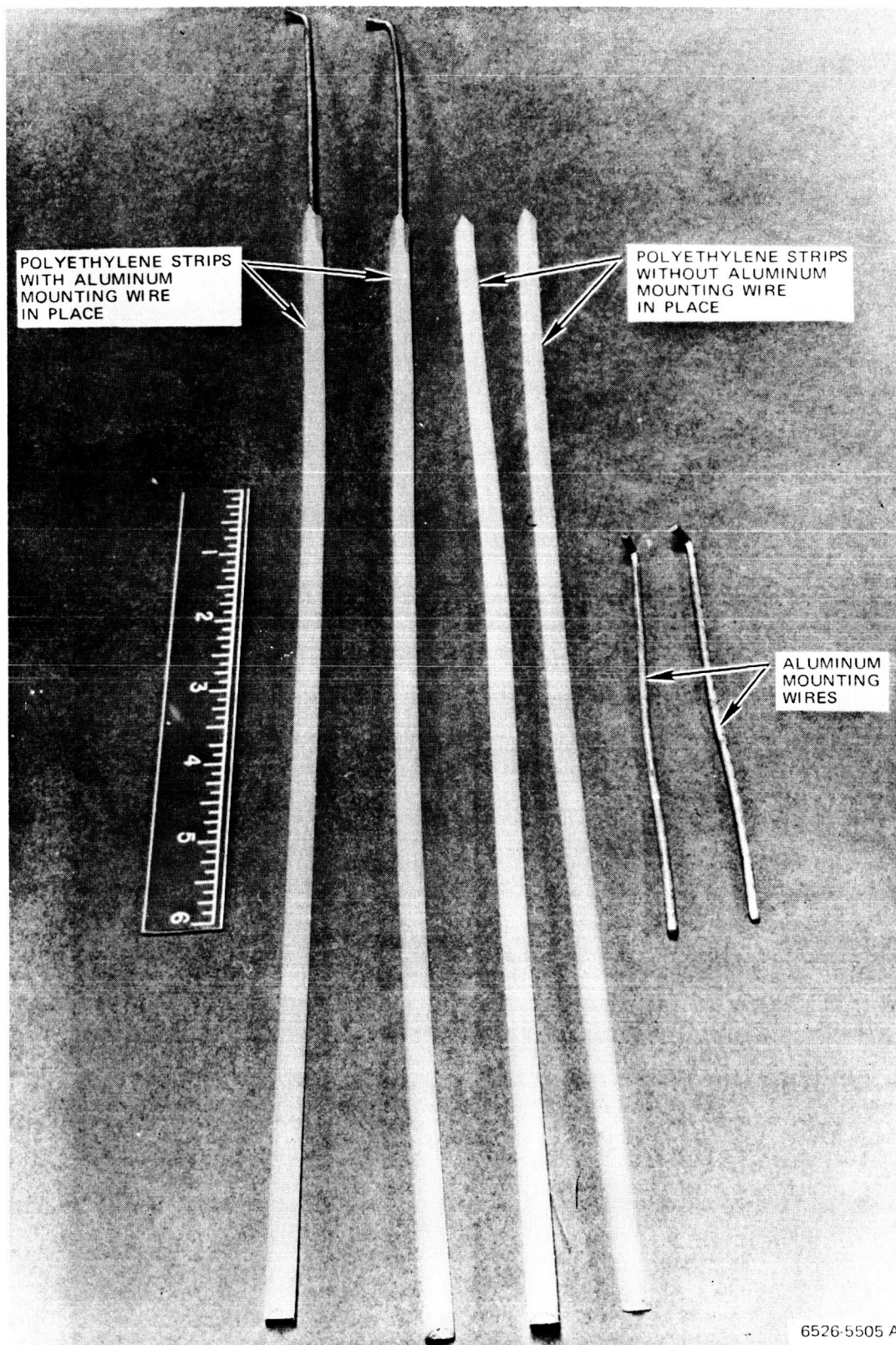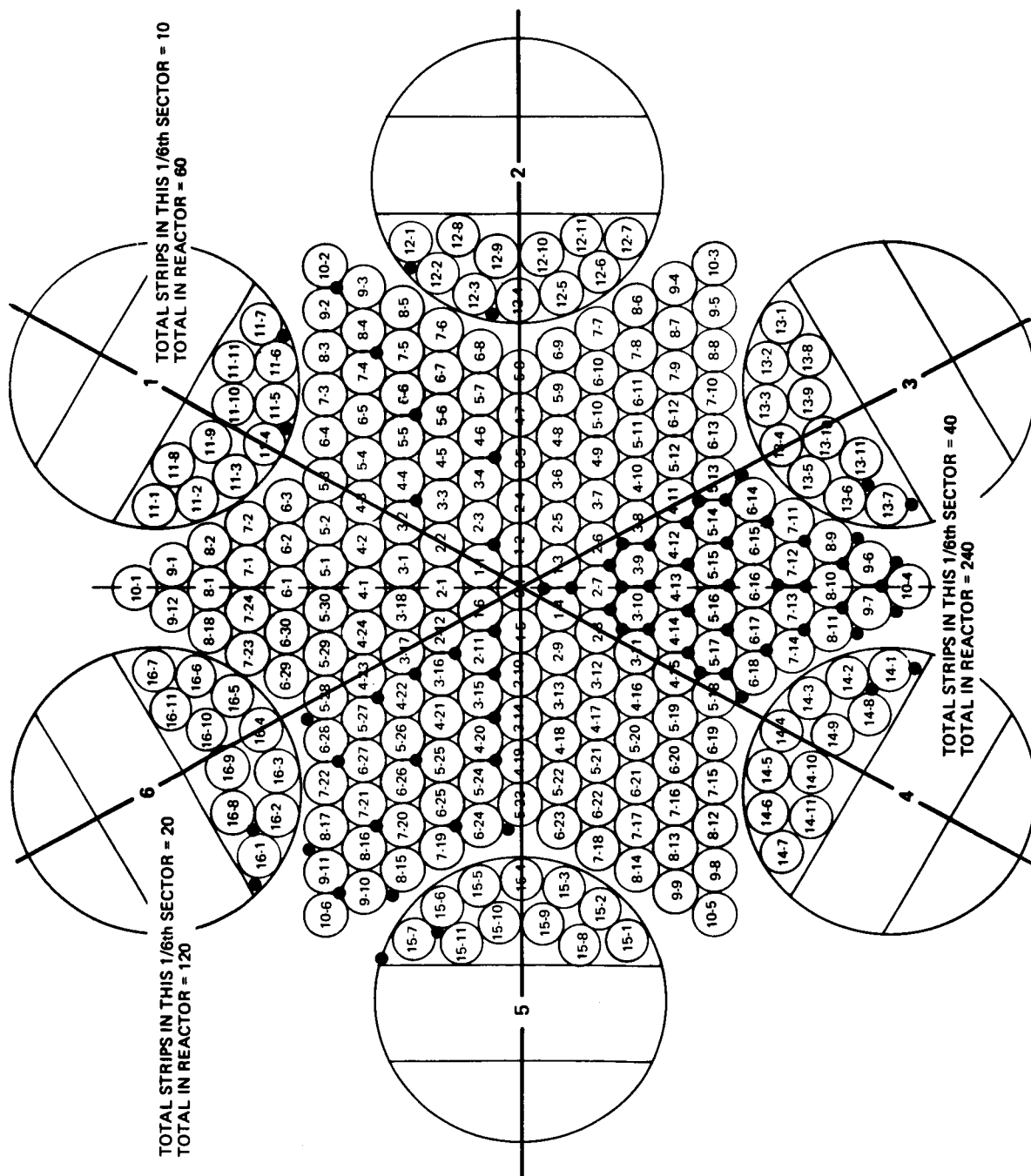ALUMINUM
MOUNTING
WIRES

6526-5505 A

Figure 42.  Polyethylene Strips

In order to be able to insert and withdraw the polyethylene strips without disassembling the core, and to restrain the strips in the axial direction to the active core region only, an aluminum wire, 0.226 cm (0.089 in.) in diameter, was imbedded a short distance (approximately 1.27 cm (0.50 in.) into the top end of the polyethylene strip. This wire, which had an average weight of 1.438 gm, extended above the strip, through the upper axial reflector zone, and was bent at a right angle so as to rest on top of the fuel element end cap. A group of 80 polyethylene strips was weighed and yielded an average weight per strip of 6.193 gm.

Since the polyethylene strips had little or no structural strength of their own, they could not be readily installed in the core except in completely enclosed zones such as those between honeycomb tubes. Outside of those zones, of which there are 300 in the stationary core, the strips had to be held in place by small piece of tape. Since Mo filler rods occupied most of the available enclosed void space in the fuel element sector of the drums (see Figure 4), only two strips could be placed within the drum. A few experiments were conducted with polyethylene strips placed on the outer periphery of the drums, but, in general, these locations were not desirable. The experimental program called for investigating the reactivity effects of adding groups of strips up to 360 to the core in a generally uniform manner. The loading schemes employed during these experiments are shown in Figure 43. When 60 strips (0.372 kg) were added to the core, a layout corresponding to that shown in the one-sixth sector between Drums 1 and 2 was followed for all six sectors. When 120 and 240 strips (0.743 and 1.486 kg) were added, the layouts corresponding to the one-sixth sectors between Drums 5 and 6 and between Drums 3 and 4, respectively, were followed for all six sectors. For 360 strips (2.229 kg), all of the remaining interstitial positions fully contained within the stationary core only (no peripheral locations) and not filled in the 240-strip layout were used. Thus, in the final layout of 360 strips, a total of 24 strips was located in the six drums and 336 strips in the stationary core.

c. Reactivity Worths of Polyethlene in a Core with 80.25 kg of Ta

The experimental plan called for (1) measuring initially the reactivity effect associated with adding 60 polyethylene strips to Core 6.0, (2) removing 2 uranium wires from each of the 247 fuel elements, and (3) adding 300 additional

Figure 43. Polyethylene Strip Loading Scheme

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TOTAL STRIPS IN THIS 1/6th SECTOR = 10
TOTAL IN REACTOR = 60

TOTAL STRIPS IN THIS 1/6th SECTOR = 40
TOTAL IN REACTOR = 240

TOTAL STRIPS IN THIS 1/6th SECTOR = 20
TOTAL IN REACTOR = 120

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polyethylene strips to bring the total to 360. With 360 strips in the core, the critical mass was to be determined. The results of these measurements are shown in Table 2 and correspond to Cores 6.2, 6.3, and 6.4. In that table, the polyethylene addition is expressed in mass units for ease in calculational comparisons.

The task of adding the first 60 polyethylene strips to Core 6.0 was actually carried out nonuniformly in two steps of 30 strips each. The task of adding 300 additional strips was actually performed by adding, after the 2 uranium wires were removed from each element, a group of 60, a group of 120, a group of 60, and, finally, another group of 60. For these intermediate steps, only changes in reactivity were measured (as opposed to absolute values) and these measurements were made only when the reactor was critical. The initial removal of 2 wires rendered the reactor subcritical. The results are given in Table 18 in

TABLE 18

SPECIFIC WORTH OF POLYETHYLENE

| Polyethylene Addition Interval (Strips) | Mass Change (kg) | Mass in Core (kg) | Reactivity Change (¢) | Specific Worth | |
|---|---|---|---|---|---|
| | | | | (¢/Strip) | (¢/gm) |
| 0 to 30 | +0.186 | 0.186 | 32.0 | 1.07 | 0.173 |
| 30 to 60 | +0.186 | 0.372 | 48.6 | 1.62 | 0.262 |
| 240 to 300 | +0.372 | 1.858 | 67.9 | 1.13 | 0.182 |
| 300 to 360 | +0.372 | 2.229 | 60.0[*] | 1.00 | 0.161 |
| 360 to 240 | -0.743 | 1.486 | 132.9 | 1.11 | 0.179 |
| 240 to 120 | -0.743 | 0.743 | 136.3[†] | 1.14 | 0.184 |
| 120 to 0 | -0.743 | 0 | 128.1[†] | 1.07 | 0.173 |
| 0 to 120[§] | +0.743 | 0.743 | 145.4[†] | 1.21 | 0.196 |
| 120 to 240[§] | +0.743 | 1.486 | 135.8 | 1.13 | 0.183 |
| 240 to 360[§] | +0.743 | 2.229 | 131.4[**] | 1.10 | 0.178 |
| | | | Average | 1.16 | 0.187 |

*Average of two measurements
†Average of 5 values
§2 Ta wires added to each fuel cluster
**Value adjusted by a 29.4¢ loss in reactivity

which, in addition, the average worth of each strip of polyethylene is tabulated in terms of single strips and per gram. The anomalously high value for the interval between 30 and 60 is attributed to the fact that the first 30 strips were added in one-half of the core and the next 30 in the other half of the core. Thus, some flux tilting would occur. However, even on the basis of a total of 60 uniformly distributed strips, the average worth per strip would appear to be somewhat high relative to the other values.

With 360 strips in the core (2.229 kg), the core-averaged worth of uranium was found to be 51.4¢.

With the reactor fully loaded with polyethylene (360 strips — 2.229 kg) and 6 rods and 5 U wires in each element, a series of reactivity measurements was conducted by removing the polyethylene in three steps of 120 strips (0.743 kg) each. Since the removal of the second group of 120 would render the reactor subcritical, provisions were made to permit the installation of a $Cf^{252}$ source at the center of the core. This core adjustment consisted of replacing the standard fuel element in Position 0-1 by two proton-recoil fuel elements, each containing a cluster of six uranium rods. One element was loaded in the upper half of the core and the other element in the lower half of the core. The 3.82-cm (1.5-in.)-high cavity that existed between the elements at the core center contained the $Cf^{252}$ source. The loss in fuel caused by this adjustment amounted to 0.0905 kg, and a reactivity change of 10.8¢, as shown for Core 6.5 in Table 2, was observed.

With the proton-recoil elements in place and an excess reactivity of 183.0¢, the first group of 120 polyethylene strips was removed to produce a polyethylene loading (1.486 kg) corresponding to that depicted in the one-sixth sector between Drums 3 and 4 of Figure 43. This removal reduced the reactivity to 50.1¢ and indicated a worth of 132.9¢ for 120 strips (refer to Cores 6.5 and 6.6 in Table 2).

Before proceeding with the removal of another group of 120 polyethylene strips, a normalization experiment was conducted for the source multiplication technique. This normalization consisted of banking all drums equally to determine the critical position (21°35′), then banking all drums to 30, 40, and 50°, the degree of subcriticality being determined at each of these positions by inverse kinetic methods. The measured reactivities were derived to be -45.2,

-113.7, and -201.0¢, respectively, at these three positions. The Cf$^{252}$ source was then installed, and the total counts obtained in Channels 1, 2, and 6 were recorded for 60-sec time intervals for each of the above positions. By normalizing the counting data obtained at the 30° position, in accordance with the technique outlined in Section I-F, one could obtain a source multiplication measurement of the degree of subcriticality at the 40 and 50° positions. The latter values were derived to be -113.7 and -203.0¢, respectively. These values are in excellent agreement with the inverse kinetic values; consequently, the 30° position was used as the normalization point for all subsequent subcritical experiments.

With the source still in place, the count rate was also measured for the situation in which all drums were banked to 70, 110, 150, and 180°. At these positions, the source multiplication technique indicated the reactor was 420.8, 917.2, 1,285, and 1,435¢ subcritical, respectively. If the excess reactivity of 50.1¢ with all drums full-in is taken into account, the worth of all drums banked from full-in to full-out is derived to be $14.85. This value was obtained from data from Channel 1 which is located at the bottom of the reactor. Channels 2 and 6 yielded substantially the same results.

Upon completion of the normalization experiments, a second group of 120 polyethylene strips was removed from the core and the reactor was found, by the above described source multiplication procedure, to be -94.7¢ subcritical with all drums full-in and 0.743 kg of polyethylene in core (refer to Core 6.7 in Table 2). Additional measurements were made with the drums at 21°35′, 30°, 40°, and 50°. Using the results at all of the positions, one obtains an average change in reactivity of 136.3¢ in going from 240 to 120 polyethylene strips in the core (see Table 18).

Finally, the last group of 120 strips was removed from the core, leaving the core void of polyethylene. Again, the degree of subcriticality was measured for 5 drum positions: all-in, 21°35′, 30°, 40°, and 50°. With all drums full-in, the reactor was 228.2¢ subcritical (refer to Core 6.8 in Table 2). On the basis of all five drum positions, an average change in reactivity of 128.1¢ was obtained.

## d.  Reactivity Worth of Polyethylene in a Core with 86.39 kg of Ta

With no polyethylene strips in the core, each of the 247 fuel elements were removed and two 0.152-cm(0.060-in.)-diam by 37.47-cm(14.75-in.)-long Ta wires were added to the fuel cluster in the location normally occupied by the uranium wire of the same diameter.  The total mass of Ta added was 6.1424 kg.  The total mass of Ta already in the core was 80.25 kg, thus bringing the total to 86.39 kg.

Source multiplication measurements were conducted with the core reassembled with the 2 Ta wires in place (Core 6.9).  The all-drums-in value for the system reactivity did not differ significantly from that for the previous, identical core (Core 6.8) that did not contain Ta wires.  However, the reactivity values at the other four drum positions showed an average value for the Ta of -10.4¢.

A group of 120 polyethylene strips (0.743 kg) was added to the core and the degree of subcriticality was measured to be -84.9¢ with all drums full-in (refer to Core 6.10 in Table 2).  An average measurement of the worth of the 120 strips was 145.4¢ on the basis of the five drum positions.

A second group of 120 polyethylene strips was added to the core (Core 6.11) to bring the total to 240 strips (1.486 kg), and criticality was achieved.  The all-drums-in excess reactivity was measured by drum calibration to be 49.6¢.  A comparison of Cores 6.6 and 6.11 indicates that the worth of the two Ta wires added to each of 247 fuel elements is zero within uncertainties when the core contains 240 polyethylene strips (1.486 kg).

For comparison with the previous results, a check, by means of inverse kinetics, was made on the system reactivity with all drums banked to 30, 40, and 50°.  Initially, the reactor was critical with all drums at about 22°40' and values of -38.5, -106.6, and -194.1¢ were determined for the 30, 40, and 50° drum positions.  These values are in reasonably good agreement with those quoted above.  Using these results, plus the all-drums-in excess, one obtains an average worth of 135.8¢ for these 120 strips (see Table 18).  Since no additional subcritical measurements were expected to be performed, the two proton-recoil elements in Position 0-1 were replaced by the standard element normally located in that position.  The reactivity associated with that change was again

determined and found to be of the order of 8.6¢; i.e., the difference between the excess reactivity values in Core 6.11 and 6.12 of Table 2.

A third group of 120 polyethylene strips was added to the core to bring the total mass to 2.229 kg and an initial excess reactivity of 160.2¢ was observed. This value appeared to be low by an amount of the order of 20 or 30¢ (depending upon the worth expected for the Ta wires) when compared to the excess reactivity observed in Core 6.3 of Table 2. However, no cause for this discrepancy could be found. A new check of the drum position for criticality was carried out about one day later, but the results were identical; i.e., the excess reactivity remained within ±0.5¢ of 160¢. The experimental measurements program was therefore continued and one uranium wire was removed from every other fuel element in order to derive a core-averaged worth for fuel. The removal of 1.60977 kg of fuel reduced the excess reactivity to 78.2¢. This change in reactivity yields a core-averaged worth of fuel of 50.9¢/kg, a value in very good agreement with that shown for Core 6.3.

In an attempt to verify that the excess reactivity obtained for Core 6.13 was correct, the core, as constituted for Core 6.14, was used to determine the excess reactivity (or degree of subcriticality) when 120 polyethylene strips (0.743 kg of polyethylene) were removed. Accordingly, the $Cf^{252}$ source was installed in Position 0-1 along with two proton-recoil elements, 120 polystrips were removed, and source multiplication measurements were conducted. The reactor was determined to be -61.8¢ subcritical with all drums full-in. In Cores 6.13 and 6.14, the loss in reactivity concomitant with the reduction of the fuel loading from 167.92643 kg to 166.31666 kg was 82.0¢. If this value is added to the -61.8¢ for Core 6.15, an excess reactivity of +20.2¢ is obtained. This value should be identical to that for Core 6.11, since the hypothetical core conditions are identical. However, there is a difference of 29.4¢; consequently, it appears that a systematic loss in reactivity of about this amount has been encountered and that the reactivity of 160.2¢ for Core 6.13, 78.2¢ for Core 6.14, and -61.8¢ for Core 6.15 should be increased by +29.4¢ to 189.6¢, 107.6¢, and -32.4¢, respectively, before correction for polyethylene. These are the values entered in Table 2. The critical mass of the core containing 167.92643 kg of fuel, 360 polyethylene strips (2.229 kg), and 2 Ta wires per fuel element (6.1424 kg), would therefore be 164.48 kg.
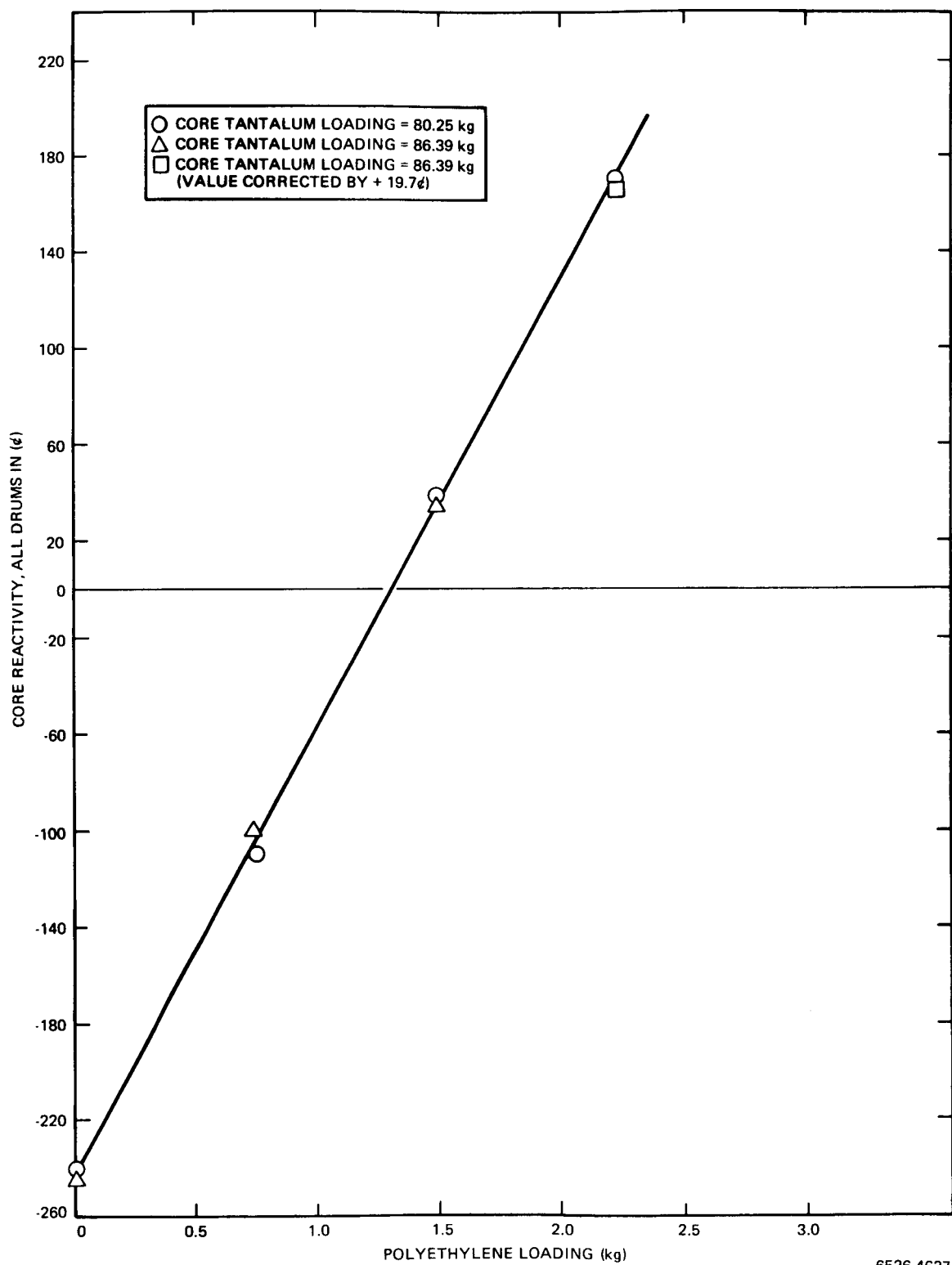
Figure 44.   Core Reactivity as a Function of Polyethylene Loading

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A plot of the core reactivity as a function of polyethylene loading for a constant fuel loading of 167.83595 kg is given in Figure 44 on the basis of the reactivity values for Cores 6.5 through 6.11, inclusive, plus the value for Core 6.13 corrected for (1) a systematic loss in reactivity of 29.4¢ as determined in Core 6.15, and (2) a worth of 9.7¢ for replacing the standard fuel element in Position 0-1 by the two proton-recoil elements. The value of 9.7¢ corresponds to the average reactivity change observed in Cores 6.3 and 6.5 and in Cores 6.11 and 6.12. The value after corrections is therefore 179.9¢ (160.2¢ + 29.4¢ - 9.7¢).

## III. DISCUSSION OF RESULTS

In general, the experimental results were in good agreement with values calculated by NASA LeRC.

Whenever, in the course of this program, a core closely duplicated in its material constituents a core that was investigated on the previous program (Reference 1), the agreement between comparable experimental results was good. Core 6.0, for example, was a reconstruction of Composition 4A as reported in Reference 1, Appendix A. The latter core had a total uranium loading of 174.96 kg, an all-drums-in excess reactivity of 139.3¢, a core-averaged worth for fuel of 51¢/kg, and a critical mass of 172.32 kg. The critical mass for Core 6.0 was 172.49 kg and its core-averaged worth for fuel was 51.2¢, both values being in very good agreement with the previous ones. The critical mass numbers are, in fact, within the 0.15% which is the accuracy required on these measurements.

Similarly, the excess reactivity values, when corrected for the differences in fuel loading, were in very good agreement for Core 2.0 on this program and Composition 2 of the previous program, both cores containing identical amounts of non-fuel material. The measured excess reactivity for Composition 2 was 186.0¢, corresponding to a uranium loading of 174.96 kg. Since the total mass of uranium in Core 2.0 was somewhat smaller (174.88 kg), its excess reactivity would be expected to be less. This situation is, indeed, found to be the case. The difference in mass (80 gm) would be expected to be worth about 4¢ on the basis of the measured core-averaged worth of uranium fuel (50.6¢) in Composition 2. Thus the measured excess reactivity value for Core 2.0 (182.5¢ before correction for polyethylene boxes) agrees very well with that predicted on the basis of the older Composition 2 data.

A somewhat less direct comparison can be made between the all-drums-in excess reactivity values for the 3-zones power-flattened cores that were constructed on both programs. On the previous program, the power-flattened core had a total uranium loading of 174.88 kg and an excess reactivity of 52¢. Upon reconstituting this core on the present program (after several intervening fuel alterations were made), a uranium loading of 175.0124 kg was achieved. Although

a fuel loading difference of only 24 gm occurred, the excess reactivity in Core 1.0 (44.6¢) was substantially less than it was in the earlier core. No explanation for the anomaly was found.

A somewhat anomalous result was also observed during this program with regard to the reactivity effects of adding Ta to the various cores. We observed during the studies on Cores 2.0 and 2.1 that 9.54 kg of Ta caused a reduction in reactivity of 17.6¢. One would expect therefore that a reactivity change of the order of -11¢ would occur during the sixth series of Cores when 6.14 kg of Ta were added. This change was not, however, observed. The reactivity worth of the added Ta was only -1.6¢ according to what was felt to be the most accurate measurement (all-drums-in). On the other hand, Cores 6.8 and 6.9 were well over $2 subcritical and, within the ±10% accuracy of a source multiplication measurement, it would be expected that an 11¢ change would be difficult to observe. At other drum positions — namely 21°35', 30°, 40°, and 50° — the Ta wire added to Core 6.8 appeared to be worth -16.0, -10.6, -10.8, and -13.2¢, respectively. The average of all these values is 10.4¢, a value in very good agreement with expectations.

When polyethylene was added to the reactor during studies on the sixth series of cores, an increased worth for Ta was anticipated since the hydrogen would be expected to soften the spectrum and increase the number of neutrons with energies in the Ta resonance region. However, a comparison of the excess reactivity values for Cores 6.6 and 6.11, values that should be good to ±1¢ (since they are measured in the delayed critical range), shows essentially zero worth for the 6.14 kg of Ta when 1.486 kg of polyethylene were present. Similar results are obtained from the data from Cores 6.5, 6.12, and 6.13 after corrections are made for differences in uranium loading. On the other hand, during the series of source multiplication normalization measurements on Core 6.6 the core reactivity values for all drums banked to 30, 40, and 50° as determined by the inverse kinetic method, were -45.2, -113.7, and -201.0¢, respectively. When these measurements were repeated in Core 6.11, which was identical to Core 6.6 except that the 6.14 kg of Ta were present, values of -38.5, -106.6, and -194.1¢ were obtained. These supposedly more accurate measurements would indicate that the Ta wires were worth about 6.9¢ with 1.486 kg of polyethylene present. The effects of polyethylene on Ta worth appear to be, in any case, rather small for the quantities of polyethylene employed in these experiments.

# IV. CONCLUSIONS

During this program, some additional experiments pertaining to the reactor physics and safety aspects of a compact, heavy-metal-reflected, fast reactor for space application were carried out. It was determined that the reactivity effects of adding a hydrogenous shield around a 3-zoned, power-flattened reactor core did not add large amounts of reactivity. A shield thickness of about 15.24 cm (6.0 in.) increased the reactivity by only about $1.0. Information concerning reactivity effects of adding Ta and W to, and varying the axial reflector thickness in, a uniformly loaded version of the reference reactor provided additional data to aid in optimizing the core design. The addition of polyethylene to another uniformly loaded version of the reference reactor served to evaluate the inherent safety of the reactor if subjected to flooding. One of the most important and interesting conclusions to this series of tasks, concerned the characteristics of a $B_4C$-controlled system. In this system, the critical mass was significantly reduced and the reactivity control afforded by the drums remained roughly as effective as it was in the case of the highly fueled drum backed by a massive Ta absorber segment.

## APPENDIX A
## CHEMICAL IMPURITIES IN CORE MATERIAL

### 1.  Chemical Impurity Specifications

Essentially, two additional core materials, not dealt with during the previous program, were utilized during this series of tasks.  Although purchase of additional quantities and forms of Ta and W were made, the previously reported impurity limits (see Appendix B of Reference 1) remained in effect.  The criterion for establishing these limits states that the reactivity effects of the impurity shall not amount to more than $\pm 1.0 ¢$.  If the impurity contributes a greater amount than this, the level of that impurity will be measured by some means in order to establish the actual amount of the impurity.

The two materials not previously dealt with in Reference 1 were polyethylene and $B_4C$.  The recommended maximum impurity levels in these two items were calculated by means of the formula

$$C_I = \frac{1.0¢}{M_H \left| \rho_{mI} - \rho_{mH} \right|} \times 10^6$$

where

$C_I$ = the impurity level in ppm

$M_H$ = the mass of the host material (polyethylene or $B_4C$) in grams

$\rho_{mI}$ = the specific worth of the impurity in $¢/gm$

$\rho_{mH}$ = the specific worth of the host material in $¢/gm$.

By the use of this formula, a maximum impurity level of 4 ppm B would be derived for the polyethylene materials.  Since the polyethylene tended to thermalize the spectrum rather severely, it was recommended that the maximum impurities for impurity materials other than boron be based upon the so-called "equivalent boron content" criterion as established by the ASA Standard for Nuclear Grade $UO_2$, Section 5.6.1.[10]  The values listed in Table 2 are derived from that standard, assuming that 4 ppm B is acceptable.  An arbitrary limit of 50,000 ppm has been selected for those materials whose capture cross sections are small.

The method for establishing the recommended impurity limits for $B_4C$ are identical to those outlined in Reference 1, Appendix B, and are also derived from the above equation, where $\rho_{mH}$ for $B_4C$ is estimated to be $-0.01 \cent/gm$. These values are also listed in Table 19.

## 2. Impurity Levels

Impurity levels in the polyethylene and in the $B_4C$ materials used in these experiments were measured at Atomics International and are reported in Table 20.

Chemical analyses as provided by the vendor for the 0.152-cm(0.060-in.)-diam by 37.47-cm(14.75-in.)-long Ta wire and for the Mo plates used in the aluminum canisters are shown in Tables 21 and 22, respectively.

## TABLE 19

### RECOMMENDED IMPURITY LIMITS (ppm)
(Sheet 1 of 2)

| Impurity | Host | |
|----------|------|------|
| | $B_4C$ | Polyethylene |
| H | 9.3 | - |
| Li | 726 | - |
| $Li^6$ | 78 | - |
| $Li^7$ | 540 | - |
| Be | 363 | (50,000)* |
| BeO | 190 | - |
| B | - | 4 |
| $B^{10}$ | - | - |
| C | - | (50,000) |
| N | 223 | 2,100 |
| O | 1,140 | (50,000) |
| F | 210 | (50,000) |
| Na | 1,140 | - |
| Mg | 256 | (50,000) |
| Al | 223 | 33,000 |
| Si | 1,140 | (50,000) |
| P | 1,140 | 55,000 |
| S | 1,140 | - |
| Cl | 1,140 | 300 |
| K | 251 | - |
| Ca | 313 | 26,000 |
| Sc | 13,000 | - |
| Ti | 271 | - |
| V | 267 | 2,800 |
| Cr | 273 | 5,000 |
| Mn | 273 | 1,100 |
| Fe | 271 | 6,000 |
| Co | 271 | 440 |
| Ni | 301 | 3,600 |
| Cu | 13,000 | 4,800 |

*( ) = arbitrary upper limit

## TABLE 19
## RECOMMENDED IMPURITY LIMITS (ppm)
### (Sheet 2 of 2)

| Impurity | Host | |
| --- | --- | --- |
| | $B_4C$ | Polyethylene |
| Zr | 13,000 | 16,000 |
| Ga | 13,000 | - |
| Ge | 13,000 | - |
| Br | 271 | - |
| Rb | 271 | - |
| Sr | 271 | - |
| Y | 271 | - |
| Zr | 271 | (50,000)* |
| Nb | 414 | - |
| Mo | (13,000) | 10,000 |
| Ru | (13,000) | - |
| Cd | 290 | 12 |
| In | 290 | - |
| Sn | 290 | 50,000 |
| Sb | 313 | - |
| Te | 313 | - |
| I | 313 | - |
| Cs | 313 | - |
| Ba | 313 | 33,000 |
| La | 341 | - |
| Rare Earths | 464 | 1.0 |
| Hf | 2,160 | - |
| W | 271 | 2,700 |
| Re | 245 | - |
| Tl | 303 | - |
| Pb | 281 | (50,000) |
| Bi | 281 | (50,000) |
| Ag | - | 480 |
| $U^{235}$ | 158 | - |
| $U^{238}$ | 251 | - |

*( ) = arbitrary upper limits

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## TABLE 20

### CHEMICAL IMPURITIES IN POLYETHYLENE AND $B_4C$

| Originator's Sample Number | Typical Sample | 0.250 Polyethylene* | 0.250 Polyethylene† | 1.0 Polyethylene | $B_4C$ |
|---|---|---|---|---|---|
| Sb | < 0.1 ND | - | - | - | - |
| P | < 1.0 ND | - | - | - | - |
| Ag | < 0.1 D | < 0.1 D | < 0.1 ND | < 0.1 ND | - |
| Al | 10 | < 2 ND | 10 | < 2 ND | < 500 ND |
| B | 0.1 | 0.3 | 0.3 | 0.2 | - |
| Ba | 0.2 | 0.2 | 0.1 | 0.1 D | - |
| Be | < 0.1 ND | < 0.1 ND | < 0.1 D | < 0.1 D | - |
| Bl | < 0.1 ND | < 0.1 D | < 0.1 ND | < 0.1 D | - |
| C | - | - | - | - | 21.7 wt % |
| Ca | 3 | 0.5 | 1 | 0.5 | 500 |
| Cd | < 0.3 ND | 0.1 | < 0.1 D | < 0.1 ND | - |
| Co | < 0.1 ND | < 0.1 ND | < 0.1 ND | < 0.1 ND | - |
| Cr | 0.1 | < 0.1 ND | 0.2 | < 0.1 D | - |
| Cu | < 0.1 D | < 0.1 D | < 0.1 | 0.1 D | - |
| Fe | 5 | 1 | 10 | 1 | 700 |
| Li | 0.1 | < 0.1 D | < 0.1 D | < 0.1 D | - |
| Mg | 0.2 | 0.3 | 2 | 0.5 | 50 |
| Mn | 0.1 | < 0.1 D | 0.3 | < 0.1 D | 50 ND |
| Mo | < 0.1 ND | < 0.1 ND | < 0.1 ND | < 0.1 ND | - |
| Na | 0.5 | 0.5 | 2 | 1 | - |
| Ni | < 0.1 D | < 0.1 ND | 0.1 | < 0.1 D | < 100 ND |
| Pb | 0.1 | 0.5 | 0.2 | 0.5 | - |
| Si | >>10 | 2 | >>10 | 2 | 400 |
| Sn | - | < 0.1 D | < 0.1 D | < 0.1 D | - |
| Ti | 3 | 0.1 ND | 2 | 0.1 ND | 50 |
| V | < 1.0 ND | < 1.0 ND | < 1.0 ND | < 1.0 ND | < 100 ND |
| K | 0.1 | 0.5 | 0.7 | 1 | - |
| Zr | < 0.3 ND | < 1.0 ND | < 1.0 ND | < 1.0 ND | 70 |
| $H_2O$ | - | - | - | - | 0.01 wt % |
| $B_2O_3$ | - | - | - | - | 0.1 |

D   Indicates detectable constituent
ND  Indicates not detectable constituent
*Order consisting of four sheets from one heat
†Order consisting of sixteen sheets from one heat

NOTE:  Values shown in parts per million unless otherwise noted.

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## TABLE 21

### CHEMICAL IMPURITIES IN Ta WIRE
(ppm)

| Impurity | Top | Bottom |
|---|---|---|
| C | < 30 | < 30 |
| Cb | 425 | 550 |
| Ca | < 10 | < 10 |
| Fe | 28 | 11 |
| H | 1.3 | 1.2 |
| Mg | < 5 | < 5 |
| Mo | < 10 | < 10 |
| N | 12 | 12 |
| Ni | < 10 | < 10 |
| O | < 50 | 50 |
| Si | < 10 | < 10 |
| Ti | < 10 | < 10 |
| W | 218 | 220 |
| Zr | < 50 | < 50 |

## TABLE 22

### CHEMICAL IMPURITIES IN Mo PLATE
(ppm)

| Material Identity | Al | Ca | Si | Fe | Cr | Ni | Cu | Mn | Mg | Sn | Co | Ti | Pb | Zr |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 394 | < 8 | 15 | < 15 | 50 | 14 | 6 | < 5 | < 10 | < 10 | < 7 | < 8 | < 10 | < 10 | 10 |
| 400 | < 8 | 11 | < 15 | 46 | 14 | 8 | < 5 | < 10 | < 10 | < 7 | < 8 | < 10 | < 10 | 9 |

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4. P. W. Benjamin, C. D. Remshall, and J. Redfearn, "The Use of a Gas-Filled Spherical Proportional Counter for Neutron Spectrum Measurements in a Zero-Energy Fast Reactor," AWRE Report No. NR 2/64, 1964

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8. J. L. Snidow, "Wall Effect Correction in Proton Recoil Spectrometers — Spherical Counter," BAW-TM-442, 1965

9. B. K. Malaviya and V. V. Verbinski, "Meeting of Specialists on Fast Reactor Spectrum Measurements and Their Interpretation," International Atomic Energy Agency, Argonne National Laboratory, USA, November 10-13, 1970 (To be published)

10. ANSI NSS-1965, Section 5.2, Paragraph 5.6

| Page | Line | Correction |
|------|------|------------|
| 2 | 19 and 20 | "manoseconds" should read "nanoseconds" |
| 8 | last line, et seq. | Sentence should read: "Whereas Composition 5A consisted of 247 fuel elements each containing 6 rods and 7 large-diameter wires of uranium, the fuel elements in the inner zone (Zone 1) of the power-flattened core contained 6 rods and only 1 wire, those in the next zone (Zone 2) 7 rods and no wires, and those in the outer zone (Zone 3) 7 rods and 4 wires." |
| 13 | 29 | "2.125" should read "2.215" |
| 39 | 32 | Correct sentence to read: "Sets of seven identical samples of each of 16 different materials . . ." |
| 47 | 13 | "avlue" should read "value" |
| 67 | 8-12 | Numbers "2," "1," and "3" should read "(2)," "(1)," and "(3)" |
| 71 | 8 | "line" should read "life" |
| 71 | 20 | $S_i = \dfrac{Ci}{\epsilon\left(1 - e^{-\lambda_i t}\right)}$ should be $S_i = \dfrac{Ci}{\epsilon\left(1 - e^{-\lambda_i T}\right)}$ |
| 74 | Table 5 | "Axial Reflector Solid Cylinder (247)" should read "Axial Reflector Solid Cylinder (494)." Also "Axial Reflector Eccentric Cylinder (247)" should read "Axial Reflector Eccentric Cylinder (494)" |
| 75 | 9 | "(0.498 in.)" should read "(0.060 in.)" |
| 75 | 28 | "0.51¢" should read "51¢" |
| 79 | 27 | Add asterisk to end of sentence |
| 79 | bottom | Add footnote as follows: *A measurement of the worth of polyethylene, which is 14.37% by weight hydrogen, was made in the center of the power-flattened core, along with a measurement of the worth of a $U^{235}$ foil (see Table 13, p 101). According to these results, the ratio of the specific worth of hydrogen (assuming the entire worth of polyethylene arises from the contained hydrogen) to that of $U^{235}$ is 33.4 rather than 80 as assumed above. |

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| Page | Line | Correction |
|------|------|------------|
| 93 | footnote | "See page 111" should read "See page 95" |
| 126 | Table 15, 5 headings | "$\varphi(\mu)$" should read "$\varphi(u)$" |
| 160 and 161 | Table 28, 8 headings | "$\varphi_{(u)}$" should read "$\varphi(u)$" |
| 179 | 5 | "0.050 in." should read "0.060 in." |
| 206 and 207 | Table 48 | Replace with corrected 2 pages which follow the Corrigendum.<br>Bars in the margin indicate changes. |
| 197 | 8 | Add clause, "where $M_H$ = mass of the host (gm)" |
| 197 | 10 | $\Delta\rho = C_I M_H(\rho_{mI} - \rho_{MH}) \times 10^6$ should read<br><br>$\Delta\rho = C_I M_H(\rho_{mI} - \rho_{mH}) \times 10^6$ |

# TABLE 48

## PHYSICAL CHARACTERISTICS OF REACTOR COMPONENTS
### (Sheet 1 of 2)

| Component | Dimensions (cm) | Unit Mass (gm) |
|---|---|---|
| BeO | 37.48 L by 1.31 D | 145.783 (7) cladding 44.577 |
| $B^{10}$ | 37.48 L by 1.34 D | 54.193 (7) cladding 44.451 |
| C | 37.48 L by 1.31 D | 86.441 (7) |
| Nb | 37.50 L by 1.27 D | 405.787 (7) |
| Mo | 37.49 L by 1.32 D | 517.830 (7) |
| Hf | 37.46 L by 1.32 D | 659.344 (7) |
| Ta | 37.48 L by 1.32 D | 845.857 (7) |
| W | 37.50 L by 1.31 D | 966.379 (7) |
| Re | 37.48 L by 1.34 D | 374.19 (7) |
| $U^{235}$ | Various assemblages of fuel rods were used | |
| $U^{238}$ | 37.48 L by 1.31 D | 937.029 (7) |
| Large capsules | 37.59 L by 1.38 OD by 0.025 W | 43.295 (7) |
| Small capsules | 7.46 L by 1.38 OD by 0.025 W | 10.240 (35) |
| Small Reactivity Samples | | |
| $Li^6$ | 5.08 L by 1.35 OD by 0.025 W | 0.258 SS 4.708 |
| $Li^7$ | 5.08 L by 1.35 OD by 0.025 W | 0.290 SS 4.708 |
| $B^{10}$ | 5.33 L by 1.30 OD by 0.016 W | 0.816 SS 4.708 |
| Hf | 4.85 L by 1.36 OD by 0.027 W | 6.564 SS 2.673 |
| Ta | 5.49 L by 1.36 OD by 0.028 W | 9.918 SS 2.674 |
| W | 5.43 L by 1.36 OD by 0.022 W | 9.208 SS 2.671 |
| Re | 5.08 L by 1.31 OD by 0.029 W | 7.962 SS 4.709 |
| $U^{235}$ | 5.49 L by 1.36 OD by 0.015 W | 6.002 SS 2.678 |
| $U^{238}$ | 5.42 L by 1.36 OD by 0.029 W | 11.217 SS 2.677 |
| Void capsule | | SS 2.677 |
| Void capsule with mandril | | SS 4.680 |
| Proton-Recoil Fuel Elements | 28.11 L by 2.16 OD | – |
| | 23.99 L by 2.16 OD | – |
| | 18.59 L by 2.16 OD | – |
| T-111 Support Sleeve | 3.81 L | 163.22 |
| Reactivity Sample Fuel Elements | | |
| Ta | | 308.62 (9) |
| $Li_3{}^7N$ | | 40.45 (9) |
| Mo | | 291.19 (9) |
| Upper Grid Plate | | 1708.8 |
| Sample Holder Tubes (Ta) | 110.33 L by 1.49 OD by 0.025 W | 234.03 |
| Mo Reflector (Top) | | 158.59 |
| Mo Reflector (Middle) | | 158.49 |
| Mo Reflector (Bottom) | | 159.81 |
| Mo Clad Simulator Tube | | 41.89 |
| Oscillator Rod | 95.30 L by 1.49 OD by 0.025 W | 202.15 |

TABLE 48

## PHYSICAL CHARACTERISTICS OF REACTOR COMPONENTS
### (Sheet 2 of 2)

| Component | Dimensions (cm) | Unit Mass (gm) |
|---|---|---|
| Fuel Rods | 15.24 L by 0.43 D | 42.275 (20)[*] |
| | 22.27 L by 0.43 D | 60.147 (20) |
| | combined 37.51 L | 102.422 |
| Honeycomb Tubes | 59.94 L(11) by 2.16 OD by 0.025 W | 181.638 (247) |
| Fuel Tubes | 58.09 L(8) by 1.58 OD by 0.025 W | 131.178 (247) |
| Lithium Nitride | 37.34 L | 41.00 (250) |
| Ta Foil | 36.83 L by 0.014 thick | 90.07 (50) |
| Ta Foil Spacer | 37.46 L by 0.007 thick | 18.78 (50) |
| W Foil | 36.68 L by 0.007 thick | 61.34 (247) |
| Hf Foil | 36.83 L by 0.008 thick | 16.66 (247) |
| Heavy U Wire | 37.47 L by 0.152 D | 13.49 |
| Fine U Wire | 37.47 L by 0.067 D also    by 0.061 D | 2.56 |
| Eccentric Mo Reflectors | 10.01 L (18) by 2.09 OD by 1.60 ID eccentric by 0.040 | 145.71 (18) |
| Solid Cylindrical Mo Reflectors | 10.02 L (5) by 1.49 D (5) | 178.95 (60) |
| End Fittings (aluminum) | - | 9.14 |
| Rubber Packing | 2.10 D by 0.32 t, 0.48 hole | 1.33 (8) |
| Ta Wire (0.28) | 37.39 L by 0.28 D | 38.61 (21) |
| Ta Wire (0.36) | 59.66 L by 0.36 D | 99.92 (17) |
| Ta Centering Ring | - | 1.74 (40) |
| Mo Wire Wrap | - | 0.251 (40) |
| Steel Wire Wrap | - | 0.105 (24) |
| Ta Absorber Segment | 60.17 L | 38,438 (6) |
| Mo Reflector Segment | 60.17 L | 41,109 (6) |
| Trapezoidal Mo Filler | 60.17 L | 2,758 (6) |
| Rod-Type Mo Filler | | |
| 3/16 | 60.10 L by 0.47 D | 108.85 |
| 4/16 | 60.12 L by 0.64 D | 195.00 |
| 5/16 | 60.12 L by 0.79 D | 302.85 |
| Scrammable Radial Reflector (Mo) | 59.74 L | 66,063 (4) |
| Stationary Radial Reflector (Mo) | 60.20 L | 67,512 (2) |
| Core Filler Segments (Mo) | 60.17 L | 1128.1 (10) |
| Pressure Vessel Mockup | | |
| 120° sectors | 59.69 L by 0.69 thick | 39,720 (2) |
| 60° sectors | 59.66 L by 0.69 thick | 20,441 (2) |
| Mo Bolts 3/8 - 24 | 5.66 L by 0.95 D | 47 (7) |
| | 6.79 L by 0.95 D | 53 (15) |
| Large Reactivity Samples | | |
| Li | 37.34 L by 1.28 D | 26.902 (7) cladding 44.739 |
| $Li^6$ | 37.34 L by 1.28 D | 21.019 (7) cladding 44.111 |
| $Li^7$ | 7.38 L by 1.28 D | 4.827 (35) cladding 10.559 |
| $Li_3^7N$ | 37.48 L by 1.34 D | 39.830 (7) cladding 45.221 |
| Be | 37.49 L by 1.31 D | 93.749 (7) cladding 44.176 |

[*]Number in parentheses denotes the number of samples used to determine the dimension or mass under discussion.